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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 5

MAGNETIC AIRBORNE DETECTOR PROGRAM

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As EVENTS of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

FOREWORD

By 1941, it was becoming increasingly clear that the airplane was a powerful weapon for antisubmarine search and attack. This was true even with no detection means other than visual sighting and no ordnance other than conventional bombs or depth-charges. Radar, particularly micro-wave radar, was to extend the efficiency of search operations for surfaced U-boats particularly during periods of low visibility and darkness. But no means existed for "seeing" a submerged submarine from aircraft. To remedy this situation the Division supported a very considerable program of research and engineering development on a reliable magnetic airborne detector [MAD] having adequate sensitivity to detect submarines positively at operationally useful ranges.

The concept of using the magnetic disturbance or anomaly created by the steel hull of a submarine to detect its presence is an old one. It had long been employed as a method of harbor protection. The problem here, however, was the difficult one of adapting these instruments, sensitive to both movement and orientation, for use on rapidly moving patrol aircraft.

In 1940 the Gulf Research and Development Company, supported by NDRC contract, undertook to adopt a sensitive magnetometer of their design to this purpose. Also the British were attempting to exploit other methods.

Division 6 promptly began a thorough study under the able leadership of Dr. L. B. Slichter, of all known methods of instrumentation. It soon became apparent that a sensitive magnetometer being developed by the Gulf Company under a separate NDRC contract offered the greatest probability of success. To develop fully the possibilities of the device in a form suitable for service use, the Division, under contract with Columbia University, set up the Airborne Instruments Laboratory where most of the further development work of this device was concentrated.

For the preparation of this report describing the activities and accomplishments of this development program, the Division is indebted to a number of persons, including H. R. Skifter, V. V. Vacquier, R. F. Simons and J. T. Wilson; and the Division 6 editorial staff of the Columbia Summary Reports Group under J. S. Coleman.

No attempt can be made here to credit all individuals and organizations which contributed to the successful outcome of this project. The basic contribution of the Gulf Research and Development Company has already been mentioned. This included the magnetometer developed by Dr. V. V. Vacquier. Mr. T. E. Shea had general supervision for some time of the development program which was under the immediate direction of Dr. D. G. C. Hare.

This development proceeded in close liaison with the Army and Navy. As conditions permitted, facilities for tests were freely provided. Special mention should be made of the vigorous interest of Admiral C. C. Rosendahl, C. O. of the Naval Air Station at Lakehurst and of the assistance which Lt. Comdr. J. B. Joyce of the Bureau of Aeronautics gave in matters of procurement and manufacture.

John T. Tate
Chief, Division 6

PREFACE

THE PRESENT volume is an attempt to summarize in orderly fashion the work done by Division 6 contractors in the development of Magnetic Airborne Detector systems. Most of the Division effort was directed towards improving and adapting the Vacquier magnetometer circuit to aircraft use. One chapter is therefore entirely devoted to explanation of some of the fundamentals governing the behavior of this form saturated-core magnetometer. While it is obviously impossible in the allotted space to treat in detail all of the research and development that have supported this investigation, it is believed that the material presented should facilitate understanding of the operation of this instrument.

The remaining chapters are concerned with the design, circuits, installation, and operation of the several instruments developed by the Airborne Instruments Laboratory [AIL] of the Columbia University Division of War Research [CUDWR] at Mineola, L. I. This program, which accounted for the bulk of the Division's activity in this field, culminated in the AN/ASQ-1 and AN/ASQ-1A systems, both of which were installed and saw active service in numerous patrol aircraft, as well as the AN/ASQ-2 dual system, designed to provide automatic operation, which was put into experimental Service use. Mention is also made of the preliminary work done on the AS/ASQ-3 system by the Bell Telephone Laboratories prior to the transfer of the project to direct Navy sponsorship.

The technical memoranda and reports upon which much of this volume is based were originally prepared by the scientists and engineers employed in these investigations. It is regretted that the limitations of space make it impossible to allocate individual credit for their many accomplishments. This material was collected and furnished to the CUDWR Summary Reports Group [SRG], by J. T. Wilson of the AIL staff.

In addition, certain new material on the behavior of saturated-core magnetometers was made available by V. Vacquier of the Sperry Gyroscope Company. Other contributions were received from E. H. Colpitts, Chief of Section 6.1, NDRC, and from R. H. Simons of AIL. Final editing and arrangement of material was largely carried out by C. B. Ellis of the SRG staff, with some assistance from J. S. Coleman of the same group. To all of the above and to the staffs of the Gulf Research and Development Company, the Bell Telephone Laboratories, the Naval Ordnance Laboratory, and the Airborne Instruments Laboratory are due the grateful thanks of the Division and its editors for their helpful cooperation in making available the source material, drawings, and photographs required for the volume, and in furnishing constructive criticism of the present work.

J. S. COLEMAN

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Chapter 1

INTRODUCTION

In the spring of 1941, Section C-4, later Division 6, of the National Defense Research Committee [NDRC] undertook the further active development of methods for detecting and locating submerged submarines. That aircraft would play an important part in antisubmarine warfare was clearly recognized. This seemingly required that aircraft should be able to detect and locate submerged as well as surfaced submarines. The recognition of this need led Section C-4 to undertake the further development of the magnetic airborne detector, the subject of this volume, and somewhat later, to undertake the development of the aircraft radio sono buoy, reported upon in Volume 14 of Division 6. With respect to the art pertinent to the project undertaken by Section C-4, reference will be limited to two developments then under way.

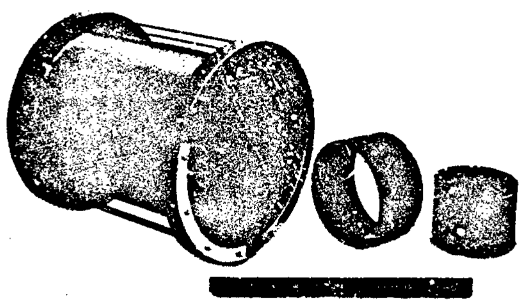


FIGURE 1. One type of main coil with trimmers developed for use in the magnetic gradiometer method.

The British, as had been learned through Navy and NDRC channels, were attempting the development of magnetic airborne gear for the detection of submerged submarines, and complete information as to their plans had been made available in part through a visit to Great Britain by American scientists early in 1941.

Even more importantly, the Gulf Research and Development Company had, in November 1940, begun work independently on sensitive magnetic devices directed toward geophysical prospecting and military objectives. This development promptly produced an instrument commonly referred to as the Vacquier magnetometer, and its employment on aircraft for submarine detection was suggested and considered.

In February 1941 the Gulf Research and Development Company arranged for the cooperation of the Sperry Gyroscope Company, and a test flight of the first model was made in a Sperry plane late in that month. Subsequent to this the Gulf Company worked under an NDRC contract under direction of Section D-3 until June 30, 1941, when, as of July 1, 1941, direction of magnetic airborne detector development was taken over and continued by the newly organized Section C-4.

In addition to continuing the work by the Gulf Research and Development Company, Section C-4 in its initial development program, under contracts with Columbia University, the Western Electric Company, and the General Electric Company, included the development of means for locating submerged submarines from aircraft by detecting the magnetic anomaly set up by the ferromagnetic mass of the submarine. The technical group assigned to this project under the Columbia University contract soon came to be designated as the Airborne Instruments Laboratory [AIL] and remained in active operation until the end of 1944.

1.1 NATURE OF PROBLEM

To detect a submerged submarine from an aircraft by the method under consideration requires the measurement of the small distortion of the earth's magnetic field caused by the presence of the submarine. The earth's magnetic field has a total intensity of about 60,000 gammas (1 gamma $= 10^{-5}$ oersted) and the distortion at a few hundred feet distance from a submarine is but a few gammas. When this development was undertaken, devices capable

of measuring variations in magnetic fields of less than 1 gamma were available, but they were not immediately adapted to use in aircraft for the following reason. Since the earth's magnetic field is a vector quantity, relative motions between it and the sensitive axis of the measuring device will produce indications of changes in field intensity, and either these indications or signals must be neutralized or these relative motions must be eliminated. From the beginning of this development, the major problem was recognized to be the elimination of the effect of those aircraft motions which give rise to spurious signals. Also, another source of spurious signals is the effect of the magnetic fields produced by the aircraft itself. To avoid spurious signals from this cause, it is necessary to select the most favorable location for the measuring device and quite commonly to provide in addition magnetic compensation. (See Chapter 6.)

How completely the major problem above was solved is indicated by the performance of the detection equipment finally developed. This had a background noise level of about 0.2 gamma under conditions of reasonably straight and level flight in a magnetically quiet area. If the magnetic fields due to the aircraft itself are properly compensated, the spurious indications resulting from rapid plane maneuvers are not over a few gammas. Thus the equipment is capable in even flight of detecting a submarine where the magnetic anomaly produced by its presence is only a few gammas. For the average submarine, this range will be about 500 feet.

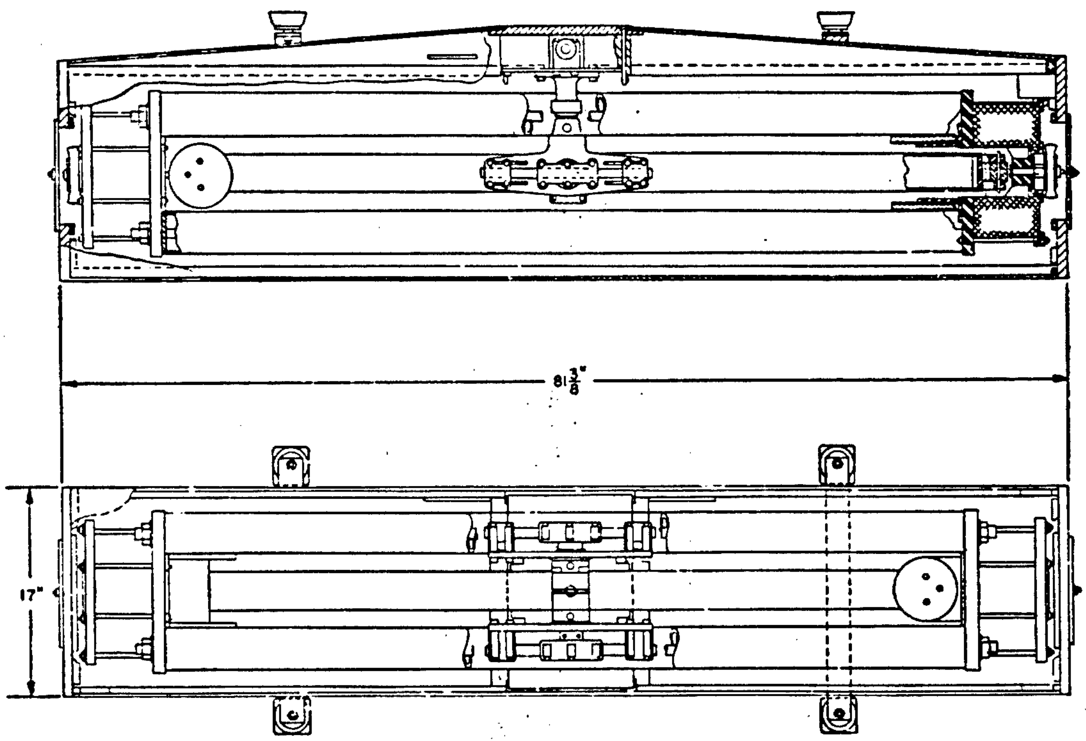


FIGURE 2. A "four-tube" type of mounting for the magnetic gradiometer coils.

1.2 METHOD PROPOSED BY BRITISH

One of two methods may be employed to determine the distortion of the earth's magnetic field resulting from the presence of a submarine or other ferromagnetic mass. The first method employs a magnetic gradiometer which when

mounted upon an airplane in flight measures the space rate of change of the magnetic gradient. In the second method a magnetometer measures directly any anomalies in the mag-

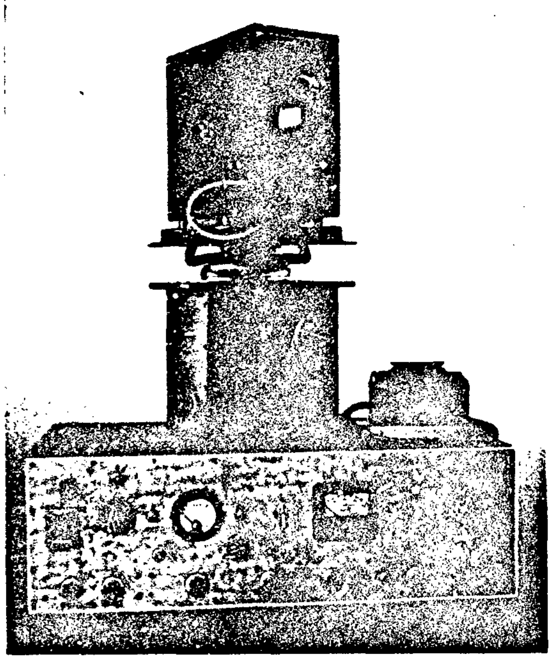


FIGURE 3. The MAD Mark I equipment.

netic field. While the first method was not developed to the stage of Service use, brief mention of it will be made at this point.

By early in 1941, the British had developed a two-coil magnetic gradiometer system capable under favorable conditions of detecting a submarine at a range of 200 feet. It was obvious to the British that this range was too small to be of operational value. The feeling expressed to NDRC representatives was that if the range could be doubled, the instrument would probably be of great value, but the inherent difficulty of accomplishing this by the British method is indicated by the following analysis.

The British experimental equipment consisted of two large inductance coils about a foot in diameter, mounted coaxially in a framework and separated about 8 feet. Each coil was as nearly as possible identical to its mate and was wound with a large number of turns, the product of the number of turns times the area of the coil in cm^2 being between 10^8 and 10^9. The two coils were connected in opposition, and with a suitable detector they form a magnetic gradiometer. As to expected performance of such a system, a submarine is very nearly equivalent to a magnetic dipole and the magnitude of such a field falls off as the third power of the distance.[1] An airplane carrying this balanced coil system will measure the space rate of change of the magnetic gradient which varies with the inverse fifth power of the distance. Thus to increase the working range from 200 feet to 400 feet necessitates an increase in the signal-to-noise ratio or in the airplane speed by a factor of 32.

To continue exploration upon the possibilities of this gradiometer method certain work was undertaken by Section C-4. Investigations indicated that a large portion of the background noise was due to deflections of the coil mountings. Therefore, the first step was to devise a coil mounting sufficiently rigid to keep the electrical axes of the two coils parallel within extremely close limits. This work on design of mountings (see Figures 1 and 2) was undertaken at the Bell Telephone Laboratories and

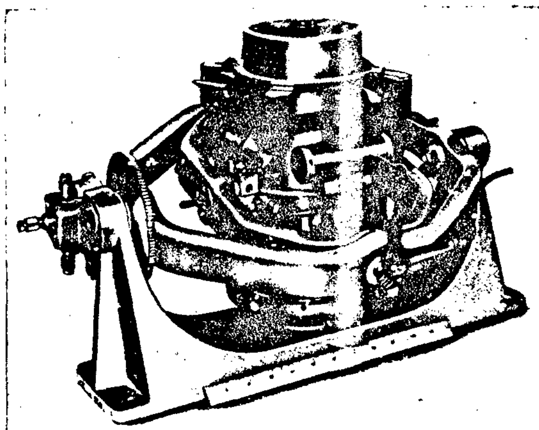


FIGURE 4. Gyroscope with magnetometer coils developed by General Electric Company.

also at the California Institute of Technology. Another step was initiated, namely, the construction of amplifiers to aid in detection of the low frequency and low voltage signals involved.

Because of the promising results being obtained with the Gulf Research and Development Company's equipment employing the Vacquier magnetometer, research on this method was terminated in November 1941.

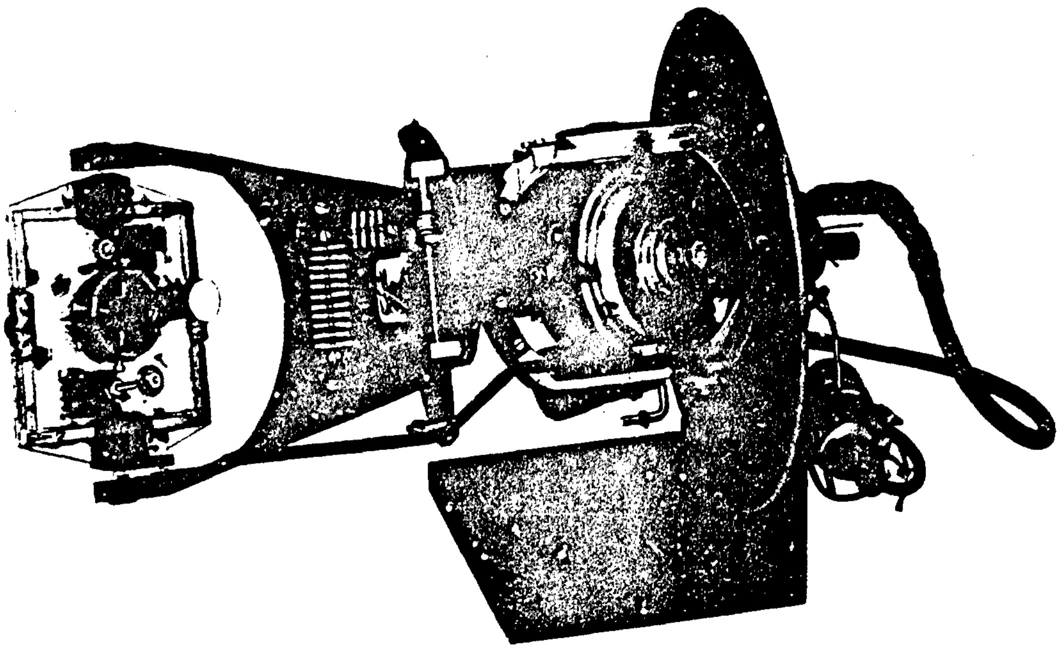


FIGURE 5. MAD Mark V head assembly.

1.3 DEVELOPMENT OF MAGNETIC AIRBORNE DETECTOR

Although later chapters of this volume describe the major developments in detail it seems appropriate to include in this introductory chapter a brief survey of the work between June 1941 and its termination. It will appear that while development was undertaken in 1941 under contracts with several agencies, after about one year NDRC development was concentrated in the Airborne Instruments Laboratory [AIL] operated by Columbia University.

1.3.1 Gulf Research and Development Company

Reference to the work of this company prior to June 30, 1941, has already been made.[2-4] In July 1941 an experimental instrument designed by the Gulf Company and utilizing a gyro furnished by the Sperry Gyroscope Company was available for test. This instrument employed the Vacquier saturated-core magnetometer and gyroscopic stabilization. Flight tests in which a representative of the Navy and of the Airborne Instruments Laboratory participated were made. These tests showed promise and indicated the direction further development should take.

Continuing development for several months, the Gulf Company produced the *magnetic airborne detector* [MAD] Mark I. Essentially it comprised a saturated-core magnetometer of the type to be described in Chapter 2, which had the sensitive element oriented in the direction of the earth's magnetic field to measure any anomalies caused by magnetic objects. The element was mounted on the frame of a gyro horizon with the angle between the magnetometer element and the gyro horizon set manually to the magnetic dip prevailing in the search area. The whole system was mounted for orien-

tation in azimuth by a shaded pole motor. The direction and amount of rotation of this motor were controlled by a second saturated-core magnetometer mounted on the gyro horizon with its axis along the magnetic east-west. When the detector element was in line with the earth's field, this magnetometer was normal to the field and therefore had no output signal. When the azimuth was not zero, the east-west magnetometer gave a signal which controlled the current in the shading field windings of the motor through suitable relays to bring the detector element again into line.

This equipment was tested in November 1941 at Quonset Point, and the flights made at that time showed that signals could be obtained from S-type submarines at altitudes of more than 400 feet. In straight and level flight of a PBY airplane the equipment, mounted in the hull, had a noise level of approximately 3 gammas. Its inherent noise level on the ground in a quiet location was about 0.5 gamma. Contrary to expectations, tests made in conjunction with our own submarines indicated that it was necessary for the equipment to function at all times during flight, including even the most rapid maneuvers. For several reasons, the noise level on the Vacquier equipment was unreasonably high when the airplane was maneuvering. The primary cause of this high background noise was that the gyroscope being held vertical by gravity would precess from the centrifugal force during a turn and give rise to a large anomalous signal when straightening out. Contributing also to this background noise were the local fields due to the aircraft's ferromagnetic and conducting parts. During the weeks following the first tests of this equipment, efforts were made with considerable success to reduce these sources of noise by "deperming" hard steel members of the plane and compensating for the effects of others. However, it was soon realized that little could be done about the inherent limitation of the gyroscope.

In December 1941 at the request of the Commanding Officer of Lakehurst Naval Air Station, the Mark I MAD was installed in a blimp and was in Service use until the late summer of 1942.

Although the limitations of performance of the Mark I were clearly indicated and the means for improvement visualized, the urgency of the submarine problem was at the moment such that Gulf was requested to defer further development and to make a number of Mark II instruments differing from Mark I only in minor improvements which could be quickly incorporated. The first Mark II unit was delivered in February 1942, and by the end of March five blimps had been equipped and were in service. A total of 14 Mark II units were produced.[5-7]

1.3.2 Bell Telephone Laboratories

The first activity of BTL as already stated concerned the two-coil magnetic gradiometer.[8]

When it became clear to all involved in this development that the methods employed for stabilizing the magnetometer, as for example in the Mark I MAD, were inadequate, development of methods for using the magnetic field alone to control the stabilization of the magnetometer were undertaken by several of the Section's contractors. The BTL work resulted in the development of a magnetically oriented instrument, using saturated-core magnetometers of the second harmonic type. The BTL development of this instrument, known as the Mark X MAD, was continued under NDRC direction to the stage of laboratory and field tests upon a working model. Development and design for manufacture of this instrument was continued by BTL under a Navy contract with the Western Electric Company and by the Naval Ordnance Laboratory, and about 50 units were produced for possible Service use.[9-16] The system was eventually called the AN/ASQ-3.[a]

1.3.3 Research Laboratory, General Electric Company

As was mentioned above, the initial program of Section C-4 made contractual provision for development by the General Electric Company.

Under the General Electric contract a limited

[a] Field comparisons of AN/ASQ-3 and the AIL type AN/ASQ-1 described below are given in references 17 to 20.

consideration was first given to the two-coil magnetic gradiometer method.[21]

The principal effort of the General Electric Company related to development of an instrument to overcome limitations of the Mark I. This employed a magnetometer coil of special design with Permalloy core mounted on an electrically driven gyroscope (Figure 4), with means for holding the common axis of coil and gyro parallel to the earth's magnetic field. These consisted of a pair of Permalloy magnetometers perpendicular to each other and to the axis of the gyro, the magnetometer outputs being amplified and made to actuate control apparatus. For some of the work a d-c amplifier was used whose stages consisted of Permalloy saturable reactors similar to the magnetometers, instead of vacuum tubes. Development of this particular apparatus was terminated before complete tests were made.[22]

The General Electric Company also made an exploratory investigation of the possibility of employing a rotating "earth inductor" as a magnetometer.

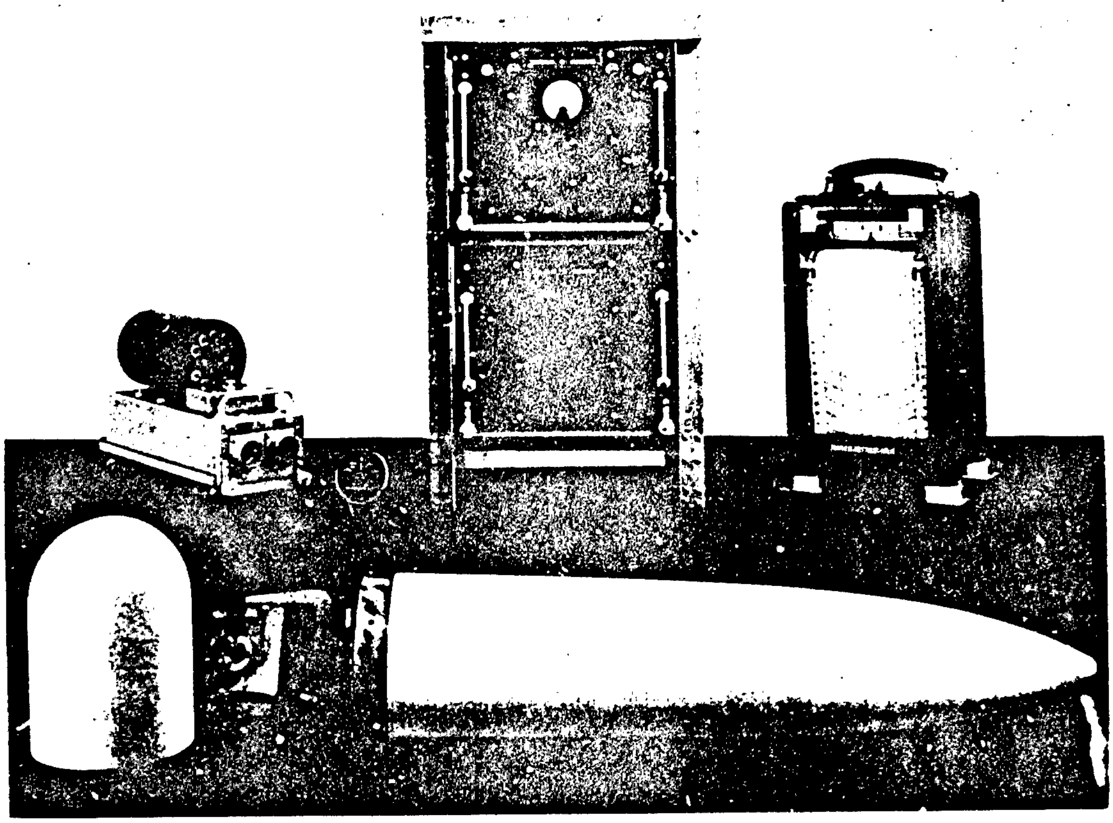


FIGURE 6. The AN/ASQ-1 magnetic airborne detection equipment.

1.3.4 Columbia University—Airborne Instruments Laboratory

Development work began under a Columbia University contract in June 1941, and after about the middle of 1942 practically all MAD development work under NDRC direction was concentrated in the Airborne Instruments Laboratory.[23-26] During the first year when development was also being undertaken by other groups this Columbia group not only carried on experimental work of its own but also did testing and

cooperative work for the other groups engaged on the same problem.

Consideration of aircraft operation and experience with early MAD models had indicated the need for intensive development of methods[27] for stabilizing the magnetometer heads. Development of two methods was for some time continued by the Columbia group.

Gyroscopic Stabilization—MAD Mark V

While magnetically stabilized equipments referred to later were being studied and developed, further research was carried out on gyroscopically stabilized magnetometer heads.[28] This research resulted in the development of an equipment designated MAD Mark V. The method employed was in large part that suggested by A. W. Hull of the General Electric Company, and the experimental development was carried out by the Sperry Gyroscope Company under contract with Columbia University.

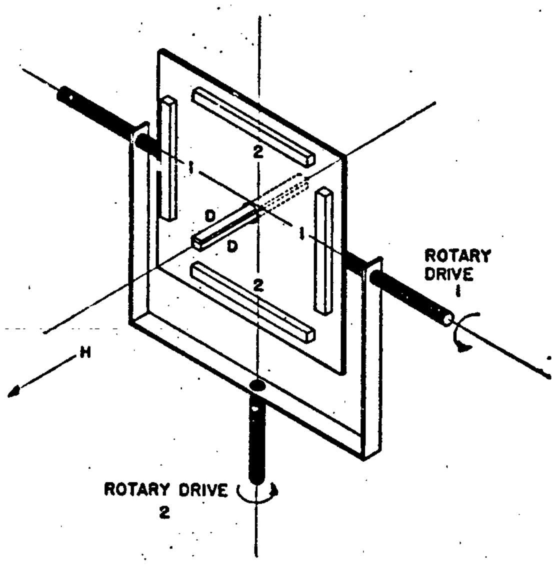


Figure 7. Schematic diagram of a magnetically stabilized magnetometer head.

As to the apparatus elements employed, a square-head magnetometer group, similar to those employed in the MAD I and Mark II, was mounted with a modified gyro horizon in a two-axis gimbal system so arranged that the detector magnetometer axis was maintained parallel to the spin axis of the gyroscope. (Figure 5.) The outputs of the two orientor magnetometers were used to control the exhaust jets of the gyroscope, thereby determining the orientation of its spin axis and thus the position of the detector magnetometer. This equipment was tested in September 1942, and although it was ultimately perfected so that its performance matched that of the equipment in production it was considered not to be well adapted for quantity production and further development was dropped.

Magnetic Stabilization

The MAD Mark IV and Mark IV B-1 systems and the resulting production models Mark IV B-2[29-33] and AN/ASQ-1 (see Figure 6) were based on magnetic stabilization of the magnetometer head without the use of any gyroscope. Figure 7 illustrates the principle schematically. The magnetometers 1-1, connected as a pair in a bridge circuit for greater sensitivity, are arranged to produce a signal whenever there exists a component of H parallel to their lengths. The signal voltage is fed to an amplifier-modulator which drives a servo motor connected to shaft 1. The sense of the resulting rotation is arranged to be such as to reduce the field component along the magnetometers to zero. Magnetometers 1-1 in this manner continuously counteract any rotations of the airplane and maintain themselves always perpendicular to H. Similarly the magnetometers 2-2, through an amplifier-modulator, actuate a servo geared to shaft 2 so as to maintain themselves perpendicular to H. The detecting magnetometers, D-D, being supported normal to the plane of 1-1 and 2-2, are therefore maintained parallel to H despite the motion of the airplane.

Further System Improvements

As a result of research on all the system components the AN/ASQ-1A production model included the following improvements.

1. A very steady voltage regulator of the cathode-loaded type for supplying power to the system.

2. A highly stable bridge-type driver-oscilla-

tor for the magnetometers employing a silicon carbide varistor as the stabilizing element.

3. Use of sine wave voltage of a single frequency for driving all the magnetometers instead of the previous pulse system,[34] which was noisy.

4. Biasing methods for precise electrical balancing of the four orientor magnetometers.

5. A lightweight motor system for the magnetometer head servos.

6. A universal magnetometer head whose suspension system permits its use in the equatorial regions of small magnetic dip—during maneuvers of the airplane in these areas the leads to the magnetometers will become tangled if the simple suspension of Figure 7 is used.

Considerable progress was also made in reducing the weight of the system and making it more compact, especially the magnetometer head assembly. Although 270 copies of Mark IV B-2 were installed in aircraft during the war, it is chiefly the later model AN/ASQ-1 and its variations which will be described in this volume.

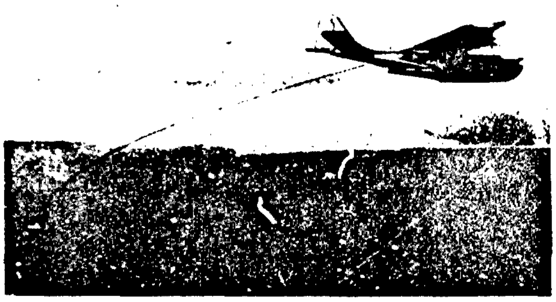


FIGURE 8. Towed bird arrangement of MAD installation.

During October and November 1942, audible signal generators for attracting the attention of MAD operators were investigated. These devices included means of producing a tone the pitch of which varied with the amplitude of the MAD signal. The project was discontinued because it was found that the operators tended to rely upon the sound signal to the total exclusion of the more reliable signals provided by the recording milliammeter.

COMBATING MAGNETIC NOISE

The limit of sensitivity of the MAD system in use is set by the level of magnetic noise prevailing. As will be discussed more fully in later chapters, the two greatest sources of such noise are (1) the small-scale hysteresis effects in the magnetometer cores and (2) the variable fields arising from magnetized portions of the airplane or metal parts in which eddy currents are induced by the airplane's maneuvers.

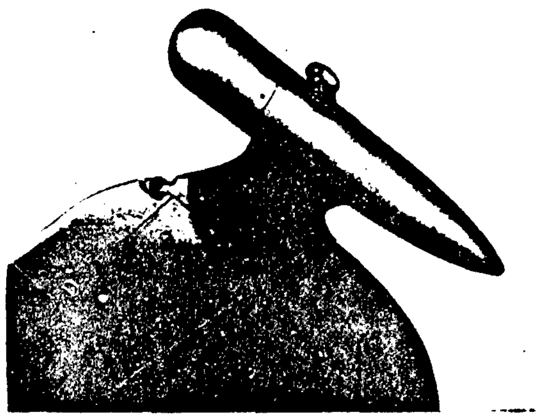


FIGURE 9. AN/ASQ-1 magnetometer and servo assembly attached to wing tip by means of a fairing.

The magnetic core noise was reduced, though not eliminated, by very careful handling and strain-free mounting of the Permalloy strips for the cores. The maneuver noise was reduced by two approaches in different systems. In one, the towed bird system, the complete magnetometer head assembly was placed in a nonmagnetic housing towed by a cable sufficiently far behind the airplane to be free from its magnetic perturbations, as shown in Figure 8. The other scheme was to mount the sensitive head on the wing tip or tail, as far as possible from most of the metal in the plane, and then to install compensating devices in such positions as were found by experiment to cancel the magnetic fields of the airplane (see Figure 9). Chapter 6 describes these methods in detail.

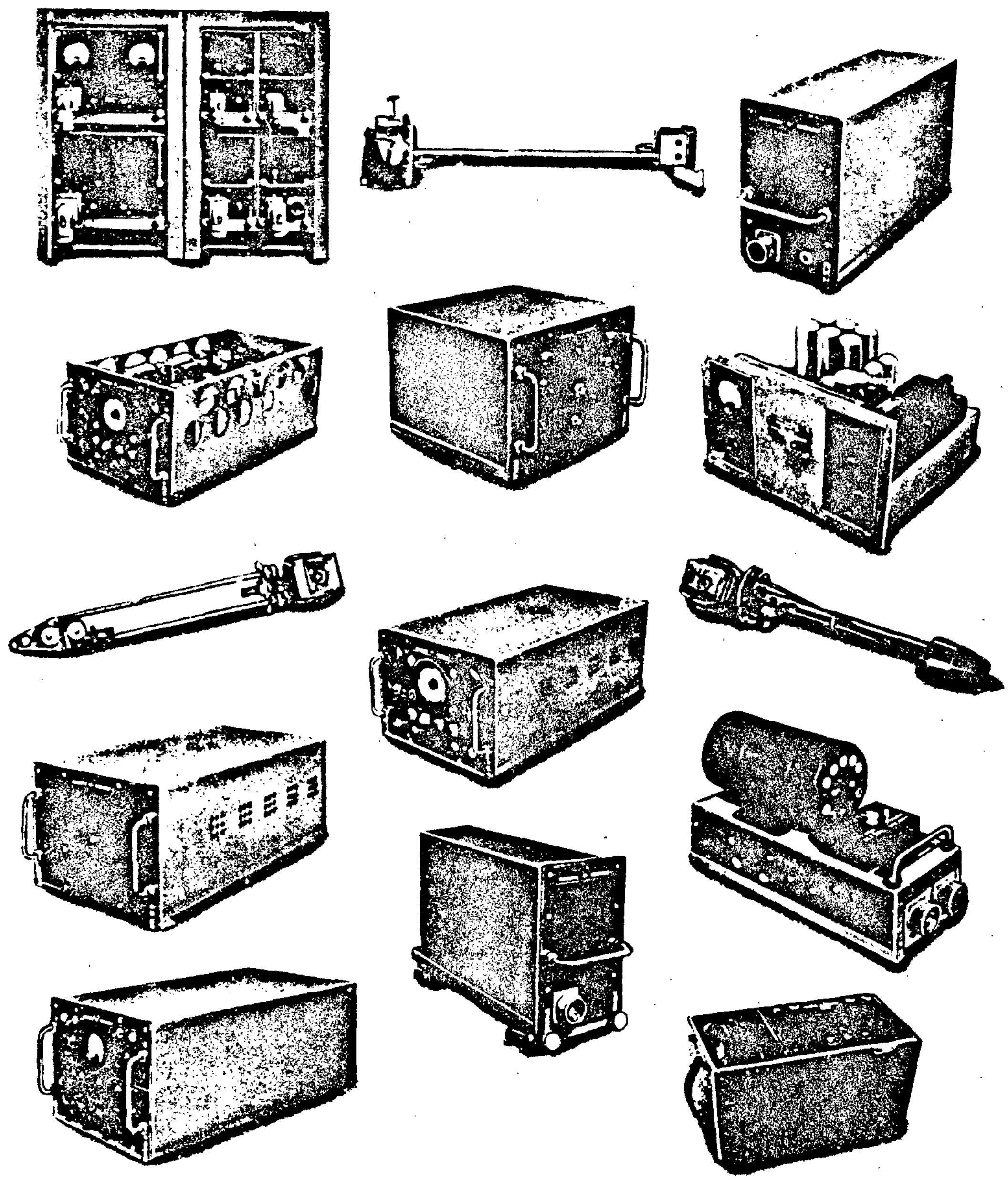


FIGURE 10. Equipment developed and produced at Airborne Instrument Laboratory.

1.4 MAD AUTOMATIC BOMB CONTROL

In the late summer of 1942, it was decided to investigate MAD equipment at AIL in connection with retro-fired projectiles for vertical bombing. This necessitated changes in the pass-band characteristics of the Mark IV B-2 in order to reduce the time between the passage of the aircraft over the target and the production of a peak signal. At about the same time, it was proposed to provide means for utilizing the output signal from an MAD equipment for the automatic release of projectiles. A tripper triggered by the signal was to complete appropriate firing circuits after a time delay so that the retro-fired projectiles would be released directly above the target.

Late in August 1942, an earlier idea was revived which proposed using two separate MAD equipments to obtain the relative lateral positions of the aircraft and the object. For this purpose two magnetometer heads were to be separated laterally in the aircraft with the output signals from the two equipments operating a single indicator which would give quantitative data as to the lateral error made in passing over a target. It was now proposed that the information obtained from the lateral indicator be utilized to limit the operation of a tripper so the missiles would be released only when the lateral range fell between certain predetermined limits. This system would require two complete MAD equipments in addition to the tripper and control units.

Various lateral-control units based on the principle of the right-left indicator described above were developed during September and October 1942. In these units, the signals from magnetometer heads on the two wing tips were compared in such a way as to provide information as to the lateral range, and means were provided to render a tripper (which operated on the sum signal) inoperative whenever the lateral range was too great for effective bombing. This combination of units formed the first magnetic airborne bombing system and was flown with a dual installation of MAD equipments in November 1942. It was intended to permit the automatic dropping of bombs when, and only when, a signal of requisite strength was received and the lateral range was such as to give effective results. As a later refinement, the tripper was arranged to operate either flare circuits alone or bomb and flare circuits together, depending upon the information provided by the lateral-control devices. In other words, any signal above a chosen threshold would drop a flare regardless of the lateral range, while any signal above the threshold which occurred with a favorable lateral range caused the release of bombs as well as flares.

At about the same time, right-left indicators were investigated which would give semiquantitative visual indications of the lateral range. The complete dual systems were given the Service designation AN/ASQ-2. Very little operational experience with these systems was obtained before the end of the war, but there was indication that further refinement was needed (Figure 10).

In the succeeding chapters of this volume many of the matters referred to in this introduction will be presented in a detailed manner. In addition, other matters such as training of MAD operators, nature of magnetic anomaly produced by a submarine, and uses of MAD for land objects will be discussed. A reference list of the principal types of MAD equipment made under OSRD contract will be found in the glossary.

Chapter 2

SATURATED-CORE MAGNETOMETERS

2.1 INTRODUCTION

THE SIMPLEST FORM of saturated-core magnetometer[1] is a strip of Permalloy around which is wrapped a coil carrying an alternating current large enough to saturate the metal during part of each cycle. (Other easily saturable materials may be used in place of Permalloy, if desired.) As the Permalloy core saturates, the self-inductance of the coil changes markedly during the cycle. This gives the driving current a rather complex wave form.

Now if an external magnetic field also acts on the Permalloy a different value of the current in the coil will cause saturation. This will change the phases at which the large variations in self-inductance occur and so alter the wave form of the driving current. If the arrangement is then connected to a circuit which is sensitive to changes in the wave form of the driving current it becomes an indicator of the magnetic field strength at the position of the Permalloy strip.

This effect has been used in various magnetometers and magnetic compasses for a number of years. Figure 1 presents some of the steps in the evolution of the saturated-core magnetometer.

The saturated-core magnetometer does not lend itself well to theoretical analysis because its operation depends on the nonlinearity of the magnetization curve, making it impossible to solve explicitly the equation for the voltage generated in response to the external magnetic field. Analysis can promote understanding of the physical phenomena involved, but it should be emphasized that it cannot be expected to determine design parameters with useful precision.

2.2 THEORY OF OPERATION

2.2.1 The Single-Coil Magnetometer

Let us first consider a single-coil magnetometer element driven by a strictly sinusoidal *current source*, as in Figure 2. The air core inductance of the coil will be considered negligible. If the coil with core had no inductance, then the voltage drop, V_1, across it would be purely resistive and so in phase with the exciting current. Let this be represented by curve $ACEC'E'A'$ in Figure 3. If the coil with core had an appreciable *constant* inductance the curve of V_1 would be of larger amplitude and leading the current, such as $BDFD'F'B'$.

Now the inductance of a coil with a ferromagnetic core depends upon the magnetization of the core, which in turn depends upon the instantaneous current in the coil, upon the external magnetic field (if any) and upon various dimensions of the system which are constants for any particular setup. In the absence of an external field a typical graph of magnetization versus exciting current for a Permalloy core will resemble Figure 4A. Saturation occurs for currents greater than $\pm i_s$. It is assumed that the amplitude of the driving current is substantially greater than i_s. The inductance of the coil at any instant depends on the slope of this graph since

$$L\frac{di}{dt} = N\frac{d\phi}{dt}$$

$$L = N\frac{d\phi}{di} = NA\frac{dB}{di}.$$

Figure 4B shows approximately how the inductance of the coil with core varies with current.

Referring again to Figure 3, it is evident that for values of the current greater than $\pm i_s$ the voltage will follow curve A, and for current less than required for saturation the voltage will shift to curve B. This shift will not be instantaneous because of the curvature of the magnetization curve, and it will be slower coming out of saturation than going into saturation. Consequently, the voltage across L_1 will have a wave form something like curve $ACDFEC'D'F'E'A'$.

The exact shape of this curve is very sensitive to slight changes in the experimental con-

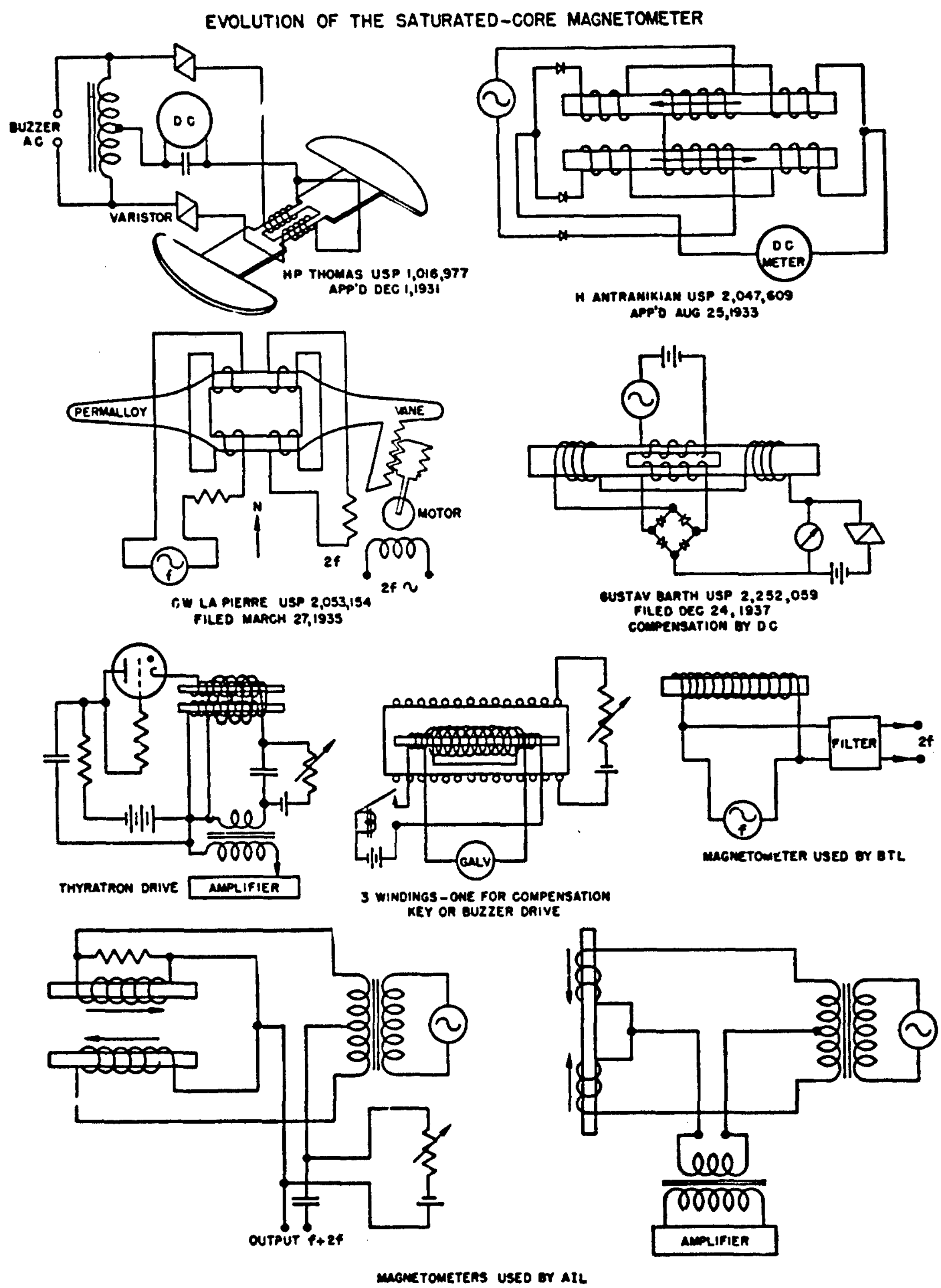


Figure 1. Evolution of the saturated-core magnetometer.

ditions. For example, let us apply a small external magnetic field parallel to the axis of the core. The magnetization curve, as shown in Figure 4C, will be shifted slightly to the right or to the left, depending on the direction of the field. Suppose it is shifted to the right. As the current decreases from its positive maximum the core will begin to desaturate earlier than for the symmetrical no-field case. This will move the point C in Figure 3 toward the *left*. As the current approaches its negative maximum the core will also saturate earlier than for the no-field case, causing point E of Figure 3 to occur farther to the left. The whole induced voltage section $CDFE$ will thus occur earlier in the cycle. Similar considerations show that the external field will cause the section $C'D'F'E'$ to move to the *right* in Figure 3. The result is shown in Figure 5A.

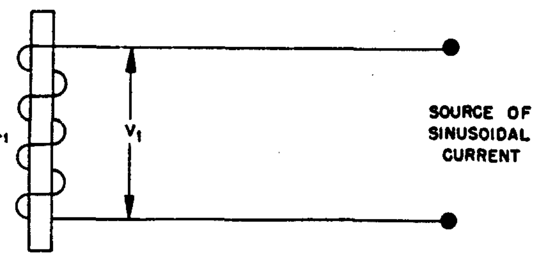


FIGURE 2. Schematic diagram of single-coil magnetometer element.

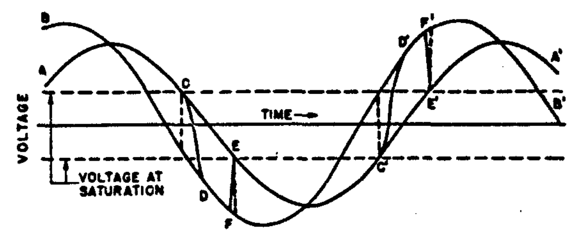


FIGURE 3. Voltage across single-coil magnetometer element.

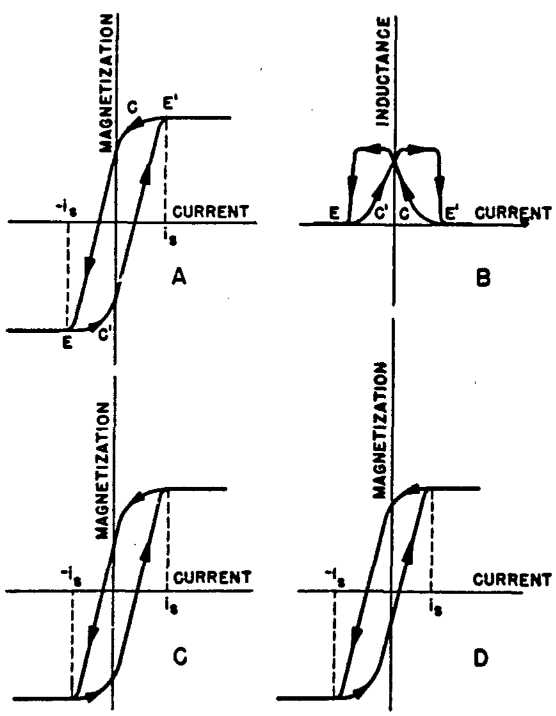


FIGURE 4. Hysteresis characteristics of saturable core elements.

If the voltage drop across the magnetometer is fed to a circuit which will respond to these shifts in the induced voltage pulses, the system becomes a sensitive detector for small magnetic fields. Subtracting the no-field curve from the with-field curve gives the *change* in output due to the field, Figure 5B. The height of these difference-voltage "spikes" is dependent on the magnitude of the external field component parallel to the axis of the core of this single-coil magnetometer. An approximate equation for the sensitivity will be derived in Section 2.2.4. It will be noted that the curve of Figure 5B contains only even harmonics of the driving frequency. Of these the second is probably

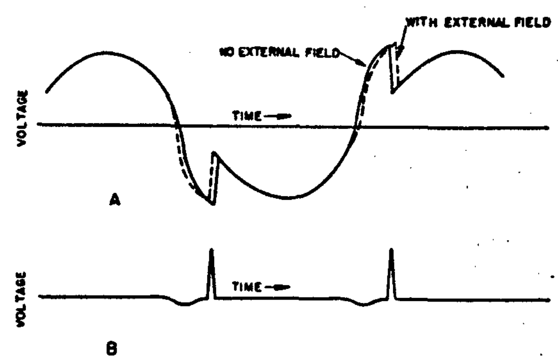


FIGURE 5. Effect of external field on single-coil magnetometer voltage.

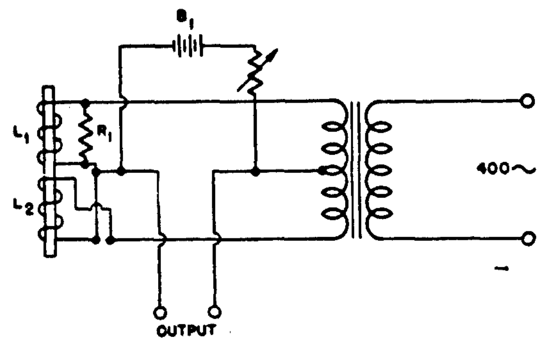


FIGURE 6. DT-1/ASQ-1, detector element schematic circuit diagram.

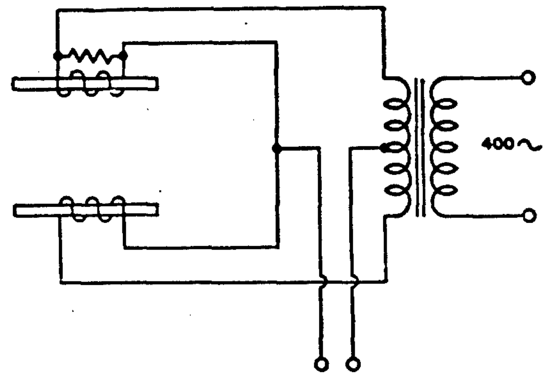


FIGURE 7. DT-1/ASQ-1, orientor element schematic circuit diagram.

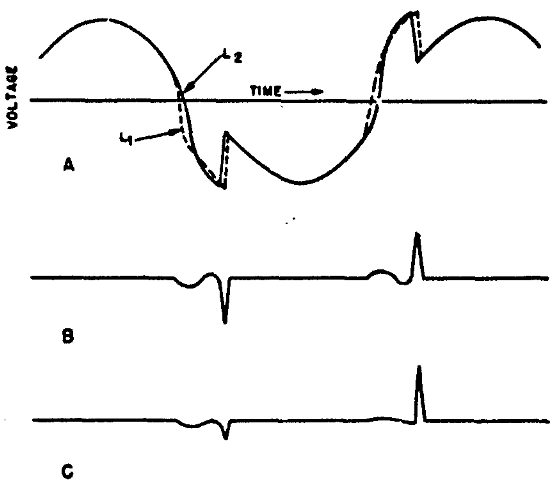


FIGURE 8. A. Voltage drop across unequal magnetometers. B. Spike pattern due to bridge unbalance, with no external field. C. Output from unbalanced bridge with external field.

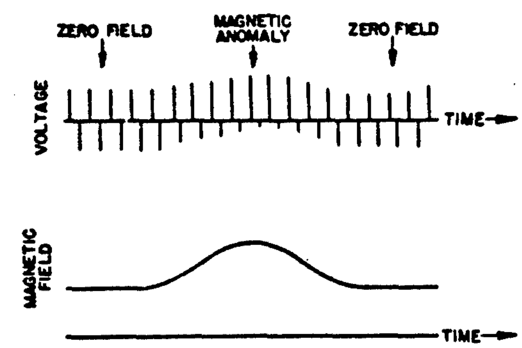


FIGURE 9. Output of magnetometer detector bridge when crossing a magnetic anomaly (schematic).

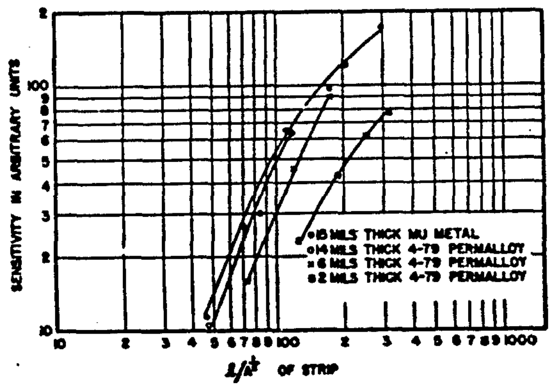


FIGURE 10. Variation of magnetometer sensitivity with dimensions of core strip.

strongest but the sharpness of the spike gives rise to many high harmonics also.

Although a single-coil magnetometer may

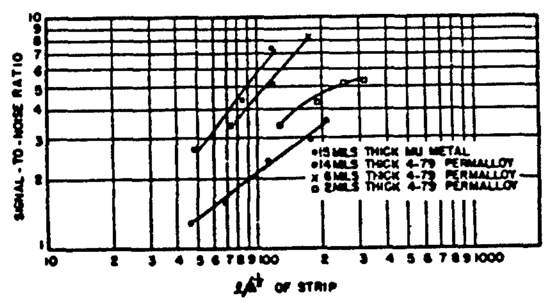


FIGURE 11. Variation of magnetometer signal-to-magnetic-noise ratio with dimensions of core strip.

serve for the detecting element as just described, greater sensitivity may be obtained by using a pair of such elements. These are con-

nected in a bridge circuit in such a way as to subtract their voltages and only send a spike pattern on to the amplifier circuits. The arrangement is described in the following section.

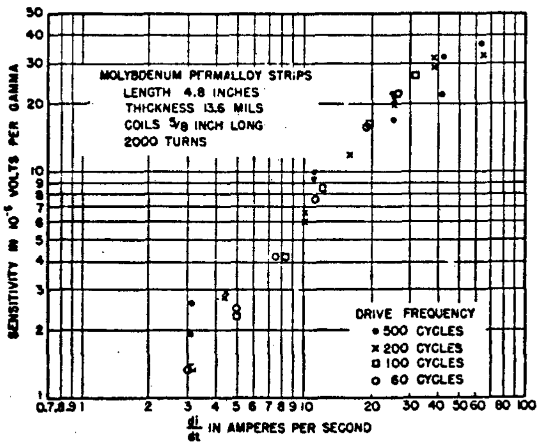


FIGURE 12. Sensitivity of magnetometer as a function of rate of change of the exciting current.

2.2.2 The Magnetometer Bridge[2]

IDEALIZED BALANCED BRIDGE

As shown in Figures 6 and 7 the two coils, now assumed identical, may be wound either on a single core or on separate parallel cores; there is no essential difference in the operation of the two varieties. The driving current is sent through both coils in series. The voltage appearing across the bridge arm is the difference between the voltage drops in the two elements. If the two elements are identical (R_1 being omitted for this ideal case) and if there is no external field, the output voltage will be zero.

The presence of a small external field will spread apart the induced voltage pulses in one of the coils in the manner of Figure 5A. However, the other coil is wound oppositely so that the magnetization curve of Figure 4C which is shifted to the left applies. This causes the induced voltage pulses to come *closer together* for this coil. The output resulting from the bridge subtraction is a spike pattern of twice the previous height (for this ideal case).

EFFECT OF BRIDGE UNBALANCE[3-5]

It is practically impossible to construct two magnetometer elements absolutely identical or to find a perfectly balanced center tap on the drive transformer, so that the bridge will not usually give absolutely zero output in the absence of external field. It turns out to be convenient in designing the detector and orientor circuits discussed subsequently to have a little unbalance in the bridge anyway. A resistor is therefore shunted across one of the coils, as shown in Figures 6 and 7, to permit adjustment of the unbalance to the optimum value.

If the current in L_1 is, for example, 99 per cent of the current in L_2 at any instant, then in every cycle the core of L_1 will saturate later and desaturate earlier than the core of L_2. This process will cause the induced voltage pulses in L_1 to be *broader* than those in L_2, as illustrated in Figure 8A. When the two voltages are subtracted by the bridge circuit the output, even with no external field, will be a set of spikes, as in Figure 8B. However, this time they are of alternating polarity (their analysis contains only odd harmonics of the drive frequency).

When an external magnetic field is applied to

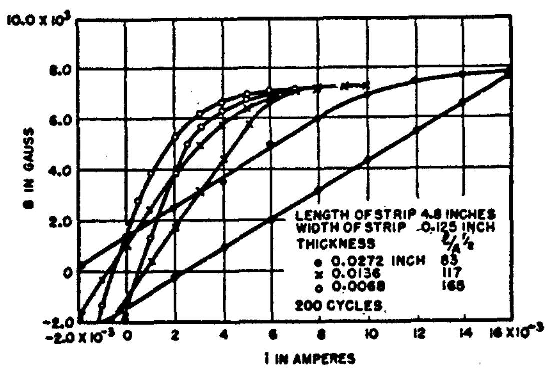


FIGURE 13. Variation of B with current for magnetometer core strips of different thicknesses (showing energy loss due to eddy currents).

this system the effect is to add the spikes caused by the field (Figure 5B) to the spikes caused by the unbalance. The result is a set of alternating spikes of unequal intensity, illustrated by Figure 8C.

2.2.3 Operation of the Magnetometers in MAD

To sum up the previous discussion: the output of the magnetometer bridge in production

AIL-MAD equipment is a series of sharp voltage pulses (spikes) of alternating polarity and equal intensity in the absence of a component of external magnetic field parallel to the axis of the Permalloy strips. The presence of a small component of external field parallel to the cores causes the alternate spikes to be of unequal intensity (see Figure 9). The difference in magnitude between the plus and minus spikes is a measure of the magnitude of the field. The positive spikes are larger for one

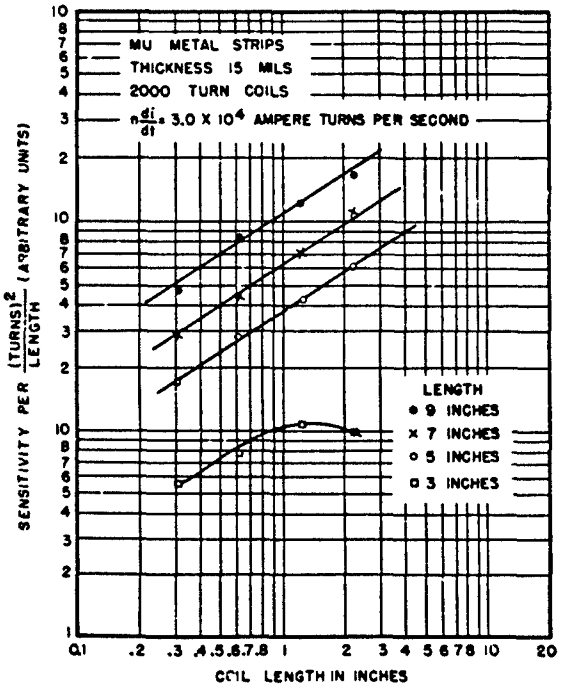


FIGURE 14. Relation between magnetometer sensitivity and coil length for various core lengths.

direction of the field component, while the negative spikes are larger for the other direction of the field component.

For the two magnetometer pairs which stabilize the head, as explained in Chapter 1, the usual orientation of the cores is normal to the ambient field. Any departure from this position due to plane maneuvers causes inequality in alternate spike heights which actuates the servo system. The magnetometer pair used as a detector is maintained by this orienting system parallel to the earth's field. The steady field of the earth is cancelled out by an adjustable direct current from the battery circuit shown in Figure 6, so as to leave the detector magnetometer sensitive only to a superimposed transient field, as from a submarine anomaly.

Throughout the above discussion a sinusoidal current drive has been assumed. It is more convenient in practice to use an approximately sinusoidal *voltage drive*. In this arrangement, as the inductance of the coil drops upon saturation more current is drawn from the source, which causes a larger voltage drop across the internal impedance of the generator. The result is a drop in measured voltage across the coil as it saturates just as in the current-drive case. Therefore the spike patterns will be the same as those already considered.

2.2.4 Sensitivity Formulas[6, 7]

The differential equation for the voltage generated in a single coil will now be set up.

Consider the magnetometer coil as a solenoid of the same length as the core, whose magnetic induction is given by the function $B(H)$. In appropriate units the voltage generated across one coil of unit cross section is

$$V = n\frac{dB}{dt}$$

or

$$V = n\frac{dB}{dH}\frac{dH}{dH_i}\frac{dH_i}{dt}, \tag{1}$$

where H_i is the value of the applied field due to a current i in the coil, and H is a function of H_i, of the demagnetization factor, and of an externally applied uniform field H_e of small magnitude. Differentiating with respect to H_e we obtain to a first order approximation

$$\Delta V = n\left[\frac{d^2B}{dH^2}\frac{\partial H}{\partial H_i}\frac{\partial H}{\partial H_e}\frac{dH_i}{dt} + \frac{dB}{dH}\frac{\partial}{\partial H_e}\left(\frac{\partial H}{\partial H_i}\right)\frac{dH_i}{dt}\right]_{H_e}. \tag{2}$$

However, since H_i and H_e are both uniform fields and affect H in the same way, we have

$$\frac{\partial H}{\partial H_i} = \frac{\partial H}{\partial H_e}$$

$$\frac{\partial}{\partial H_e}\left(\frac{\partial H}{\partial H_i}\right) = \frac{\partial^2 H}{\partial H_i^2}.$$

In this case we have

$$\Delta V = n\left[\frac{d^2B}{dH^2}\left(\frac{\partial H}{\partial H_i}\right)^2 + \frac{dB}{dH}\frac{\partial^2 H}{\partial H_i^2}\right]\frac{dH_i}{dt}H_e. \quad (3)$$

To evaluate $\partial H/\partial H_i$, consider that, in a uniform field H_i only, the field H within a needle-like strip of ferromagnetic metal is given by the equation

$$H = H_i - NI, \quad (4)$$

where I is the intensity of magnetization and N the demagnetizing factor, which depends upon the size and shape of the strip. Since $B = H + 4\pi I$ and H is small compared to I, we can substitute $B = 4\pi I$ in equation (4) and writing k for $N/4\pi$, we have

$$H = H_i - kB(H).$$

On differentiation we find

$$\frac{\partial H}{\partial H_i} = \frac{1}{1 + k\dfrac{dB}{dH}}. \quad (5)$$

By using the last expression in equation (3) we find

$$\Delta V = n\frac{d^2B}{dH^2}\frac{dH_i}{dt}H_e\frac{1}{\left(1 + k\dfrac{dB}{dH}\right)^3}. \quad (6)$$

For a long solenoid, H_i is proportional to n/l, the number of turns per unit length, and to the current i. In this case we can write

$$\Delta V = \frac{Kn^2}{l}\frac{d^2B}{dH^2}\frac{di}{dt}H_e\frac{1}{\left(1 + k\dfrac{dB}{dH}\right)^3}. \quad (7)$$

This is essentially the equation of the spike curve of Figure 5B. The result should be doubled for a two-coil magnetometer.

For a given H_e, the maximum generated voltage occurs when the product (d^2B/dH^2) (di/dt) is maximum. This means that the core should come into saturation while di/dt is still large, i.e., to achieve maximum sensitivity the cores have to be driven well beyond saturation. Beyond this, further increase in the amplitude of the excitation will not materially alter the height of the voltage spikes. Equation (7) also indicates that, except for the effect of eddy currents, the magnetic sensitivity should be linearly proportional to frequency. These deductions are confirmed by experiment.

Equation (7) has been derived for a coil of the same length as the core, whereas in the AIL magnetometers the coils were ⅝ inch long and the cores were 5 inches long for the detector magnetometers and 3.5 inches for the orienting magnetometers. It can be seen from equation (7) that for a given number of turns n, we should expect a greater sensitivity from the concentrated coils than from a distributed winding, because the length of the coil l appears in the denominator. The rate of change of flux in the portions of the strip protruding from the coil does not contribute to the generated voltage because these portions reach saturation some time after the material within the coil is saturated, although the protruding ends of the core do increase the effective permeability of the strip by decreasing its demagnetization factor. If, however, the factor n^2/l is kept constant the sensitivity increases with coil length, because more of the magnetic material reaches saturation at the same time, thus sharpening the curvature of the hysteresis curve at the point of saturation. In other words, the maximum value of d^2B/dH^2 is increased.

Presumably it should be possible to construct the voltage-time graph for the magnetometer by computing the terms entering into equation (7) point by point from the B-H curve and other data or even more directly by accurately measuring the voltage contribution of each coil and the phase shifts produced by the application of the external field. This graphical analysis has yielded qualitative results in agreement with experiment.[8]

2.3 MAGNETOMETER DESIGN FACTORS

The design factors[9, 10] entering into the construction of the magnetometers can be listed as follows.

1. The core material.
2. The cross-sectional area of the core.
3. The ratio of the core length to its cross-sectional area.
4. The *B-H* curve of the core.
5. The design of the coils.

6. The amplitude and the frequency of the energizing current.

7. The extent to which the core is laminated for reducing the effect of eddy currents.

8. Strain-free mounting of the cores.

Investigation of several core materials revealed that the nature of the material has a bearing on the residual noise of the magnetometer but has little influence on the sensitivity.

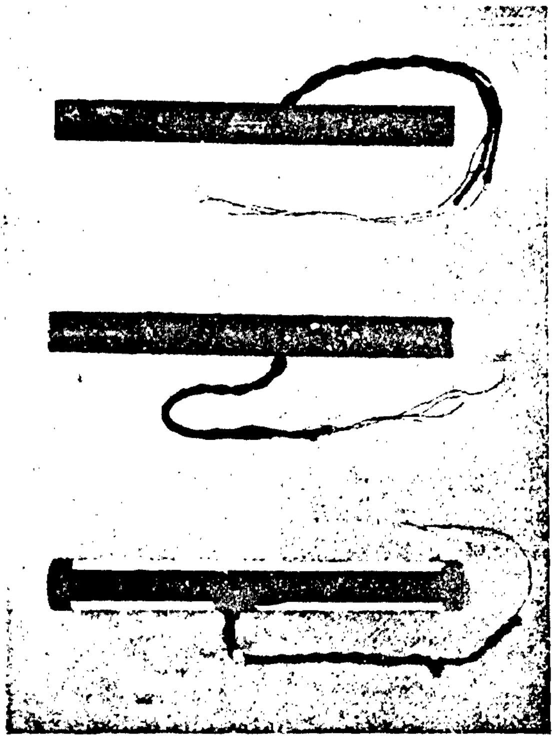


FIGURE 15. DT-1/ASQ-1 unit, detector assembly showing coils and strip.

The results of this investigation at AIL are summarized in Table 1.

The experimental curves in Figures 10 to 14 are reproduced to indicate values of the design factors. They are for cores consisting of a single strip of material. Unless specified, the cores are ⅛ inch wide; the coils, 2,000 turns layer wound with No. 40 wire, ⅝ inch long; the frequency of the drive, 400 c.

2.4 MAGNETIC CORE NOISE[11-13]

It is believed that the sensitivity of saturated-core magnetometers is limited by the failure of the core material to repeat exactly its magnetization curve from cycle to cycle. The influence of the nature of the material on the signal-to-noise ratio was given in Table 1. If

TABLE 1. Sensitivity-noise ratio for various metals as used in saturable magnetometer cores. (The units are arbitrary.)

Metal	Sensitivity	Noise	Sensitivity/noise
4-79 Permalloy			
4-4, 8-15	50	10	5
5-4, 8-14	50	9	5.6
6-4, 8-14	50	10	5
7-4, 8-14	49	10	4.9
High-mu Permalloy			
12-4, 8-14	62	22	2.8
Mumetal, M-4, 8-15	65.6	27	2.4
No. 143 Alloy, A-5-10	41	58	0.7
Perminvar, V-5-10	39	354	0.1

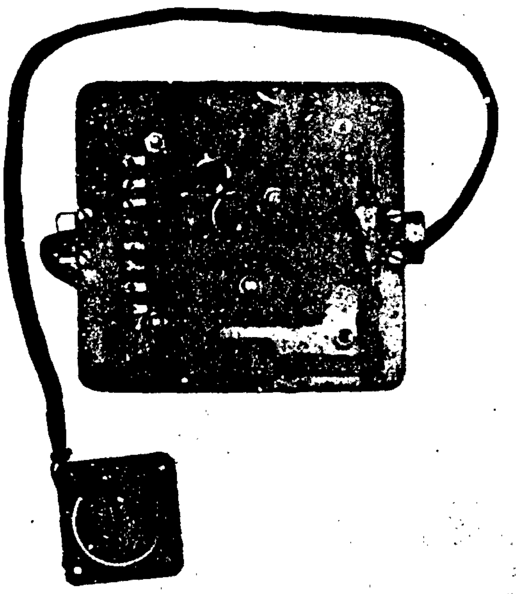


FIGURE 16. DT-1/ASQ-1, bottom view of Mycalex plate showing orientor element strips and coils.

the variations of magnetization can be attributed to Barkhausen discontinuities, then for a given material it is reasonable to expect some improvement from increasing the cross-sectional area of the core. This was done by BTL without increasing eddy current losses by rolling a sheet of Permalloy 0.001 inch thick

into a scroll-shaped core. Smaller variations in magnetization from cycle to cycle can be also expected from a magnetometer in which the core or cores are magnetized by solenoids at least as long as the cores, so that all the material is brought to saturation at the same time, and by increasing the amplitude of the driving current. These expectations have been verified by experiment.

For the standard AIL magnetometers in AN/ASQ equipment the value of magnetic noise level is of the order of 0.2 gamma. In the case of special experimental second-harmonic-type detectors, the smallest noise level reported was 0.03 gamma.

In order to achieve this low level of magnetic noise, constraint of the core material must be specially avoided. Any supports which cause bending or tension of the core strips result in increased noise. In the AN/ASQ-1 equipment the strips and coils of the magnetometer elements are supported in a wax of sufficiently high melting point as to prevent appreciable flow at the operating temperature. For further protection the whole is then enclosed in a glass tube. Figure 15 shows a detector element assembly, and Figure 16 shows the manner of mounting the orientor elements. References 14 to 18 describe the techniques used in selecting, matching, and mounting the elements.

Chapter 3

THE AN/ASQ-1 DETECTION EQUIPMENT

3.1 GENERAL DESIGN CONSIDERATIONS

THE PURPOSE of the AN/ASQ-1 system was the employment of a saturated-core magnetometer for the detection of submerged submarines from aircraft. This was accomplished by the detection of the local anomaly produced in the earth's magnetic field by the presence of the submarine. The range at which the submarine could be so detected is a function of the minimum observable anomaly. The size of this limiting anomaly or "signal" is in turn dependent upon the magnetic moment of the submarine and the level of all the various unwanted fluctuations, magnetic, electrical, or mechanical in origin, which appear on the indicator of the system.

3.1.1 Character of the Submarine Anomaly

For the purpose of approximating the way in which the strength of the anomaly field depends upon distance from the submarine, this field may be considered to be produced by a simple dipole source. To this degree of approximation the field varies as the inverse cube of the distance from the source. The value of the equivalent magnetic moment of a submarine depends upon its size, its magnetic heading, its magnetic latitude, and the state of its permanent magnetization as influenced by its previous history. The actual values of magnetic moments of submarines which were measured during the war varied from 1×10^7 cgs units to about 30×10^7 cgs units.[a] Thus, the order of magnitude of the magnetic anomaly at a distance of 400 feet from a representative submarine would be 10 gammas.[b]

The average value of the earth's field, in, say, the North Atlantic region is approximately 60,000 gammas. Bearing in mind that anomalies considerably smaller than the example quoted above must be detectable for the system to be successful, it is clear that the first requirement on the system is that it be capable of detecting and indicating an anomaly in a vector field whose size is approximately one part in 60,000 of the ambient value of that field.

At any point the resultant field is the vector sum of a constant field due to the earth and the small field due to the submarine. Even if the latter is at right angles to the earth's field it will not change the direction of the resultant vector more than about arctan 10/60,000 or 30 seconds of angle. Since the orienting mechanism will not respond to such a small variation, the detecting magnetometer will retain the same direction it had before approaching the submarine. Therefore that feature of the anomaly which will be impressed upon the detector at any point is essentially its component in the direction of the earth's field. The magnitude and variation of the magnitude with position to be expected of this quantity can be worked out mathematically[1-4] or measured with models in the laboratory, assuming the submarine to be equivalent to a magnetic dipole. Figure 1 shows a contour map obtained from model experiments in the manner to be described in Chapter 4. The submarine was assumed to have a magnetic moment of about 15×10^7 cgs units so oriented as to lead to those longitudinal, transverse, and vertical components of its moment listed in the figure. By laying a rule across such a contour map one may plot the field which must be detected by the magnetometer during any straight flight of the airplane over this submarine at 200 feet vertical separation. Figure 2 shows such a plot on another model contour map.

Since the aircraft which carries the AN/ASQ-1 equipment flies through the anomaly field of the submarine, the detection of the anomaly is a dynamic phenomenon. Figures 3 and 4, which are plotted on a time axis, show

[a] It should be noted that these moments might possibly be reduced by a factor of 10 by careful degaussing of the submarine. However, to be effective at all times the degaussing equipment would have to be carried on the submarine and kept in continuous operation.

[b] One gamma equals 10^{-5} oersted.

the results to be expected in crossing the contours of Figure 1 at 100 knots. The anomaly signal is a transient disturbance to the energy of which a frequency distribution may be assigned. The frequency band in which most of this energy lies is determined by the extent of the anomaly and the speed of the aircraft. Under typical operational conditions, e.g., aircraft speed of 120 knots and distance of closest approach of submarine 400 feet, this band extends roughly from 0.01 c to 10 c. Therefore, in attacking the problem of maximizing the ratio of signal to undesired background fluctuations or "noise," only that noise which lies in the above-mentioned frequency band need be considered.

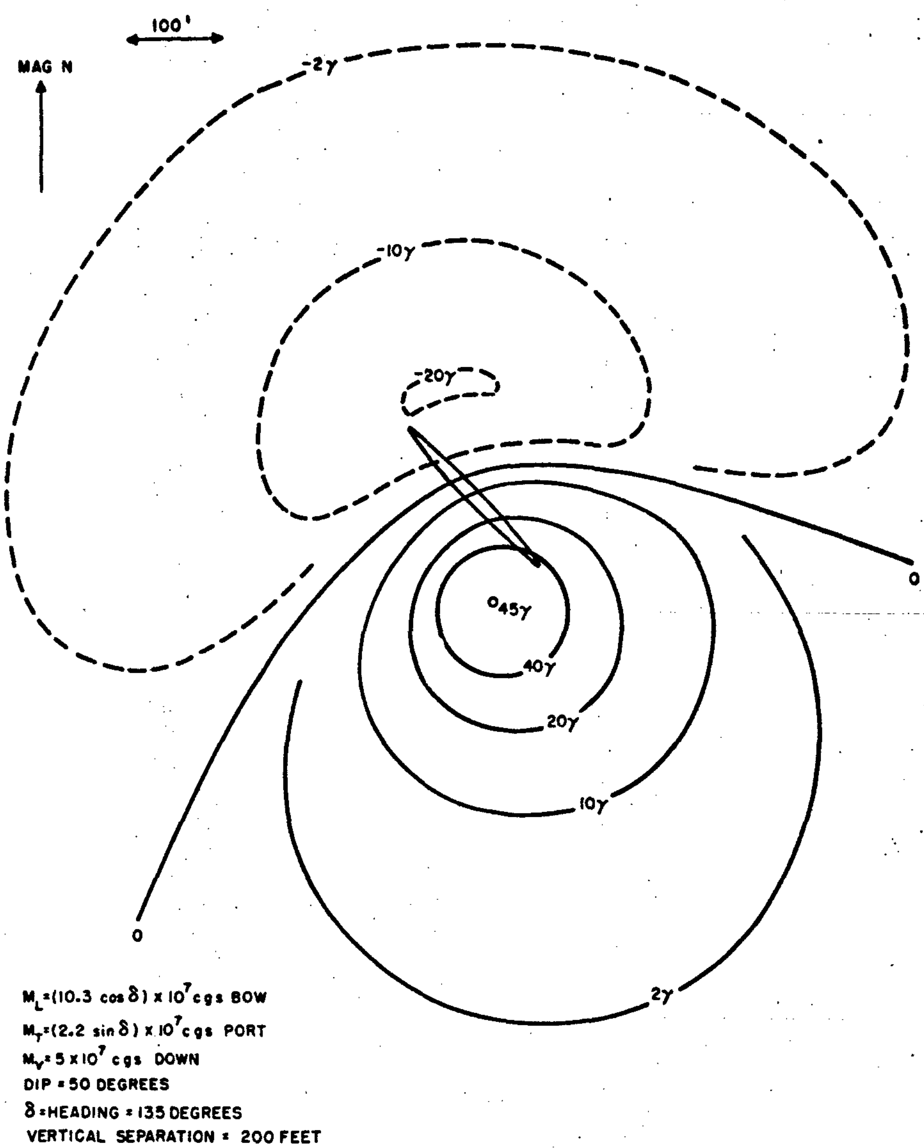


FIGURE 1. Static contour map, showing magnitude of component parallel to earth's field at 200-foot level of the magnetic anomaly due to a typical submarine model.

3.1.2 Noise Reduction

The background noise,[5] which limits the range at which a submarine may be detected, may be classified into five different types as follows: (1) natural fluctuations with time in the terrestrial magnetic field, (2) fluctuations in the output signal of the magnetometer arising from rotation of the axis of the magnetometer with respect to the direction of the terrestrial field, (3) magnetic fluctuations caused by magnetic sources close to the detection equipment, (4) random fluctuations in the output signal of the magnetometer generated in the process of carrying the magnetometer core material through successive hysteresis loops, so-called core noise, (5) fluctuations in the indicating system introduced by microphonics, fluctuations in power supply voltage, etc. A spurious signal will also occur when passing over an anomaly in the earth's field of geological origin.

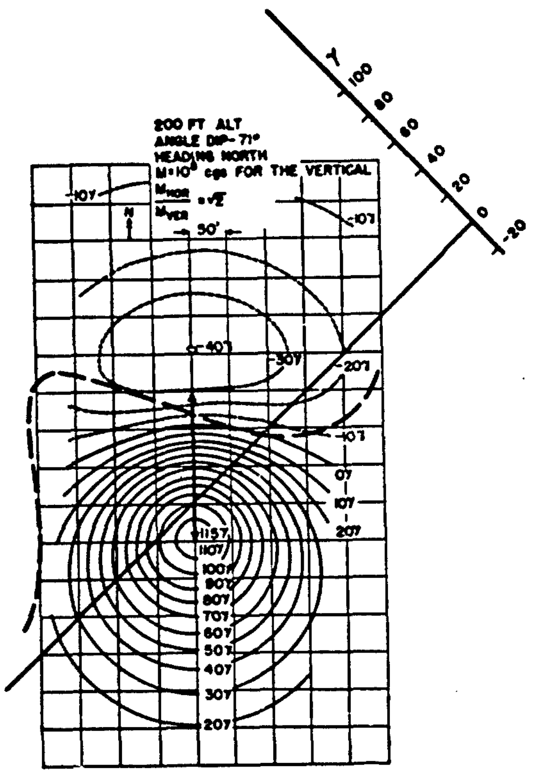


FIGURE 2. Model static contour map, with plot of field strengths encountered by a plane on a level 45° course passing over the submarine at 200-foot vertical separation. (N-S arrow 200 feet long in center of chart represents submarine.)

1. Terrestrial magnetic noise is beyond the control of the design engineer. Fortunately, it is extremely small at these frequencies except during intense magnetic storms or in the immediate neighborhood of a thunderstorm, as indicated in Chapter 7. The other types are susceptible to reduction by means of improved design.

2. In order to control fluctuations due to magnetometer motion successfully, the parallelism of the magnetometer axis and the direction of the ambient field must be maintained to five minutes of arc. A variation of this amount in angle will produce an apparent change, in the magnetic field as measured by the magnetometer, of 0.06 gamma, which is adjudged to be the maximum tolerable noise from this source. The complete electromechanical servo system must have suitable dynamic characteristics; that is, it must not oscillate of itself, it must have the proper internal damping, yet it must be sufficiently rapid in its response to accommodate the angular motions required by the maneuvers of the carrying aircraft.[6,7] One feature of the stabilizing mechanism, which is of vital significance, should be noted at this point. Since the two stabilizing magnetometers are normally perpendicular to the direction of the earth's field, they have a maximum sensitivity to rotations of the magnetometer array. This is in contrast to the signal detector, whose sensitivity to such rotation is at a minimum, because the cosine is a slowly varying function near zero degrees. Therefore, for magnetometers of the same sensitivity to change in field parallel to their respective axes, the voltage output of the stabilizing magnetometers for a given error in alignment is many times the output of the signal-detector magnetometer due to this error. It is this differential in sensitivity to orientation error which permits the above-described principle of stabilization to be used. Orientation of the detector exactly parallel to the magnetic vector, rather than at some slight but equally well maintained angle, is most important. For the detector parallel to the magnetic axis, a deviation of 1 degree decreases the measured

field only 9 gammas, whereas if it were 3 degrees from parallel, an additional degree would decrease the field about 60 gammas. Since the necessary accuracy of construction of the magnetometer head is too difficult to attain readily, small neutralizing currents are sent through the orientor magnetometers of AN/ASQ-1. These are adjusted by trial until the orientors give zero output when the detector is strictly parallel to the field.[8]

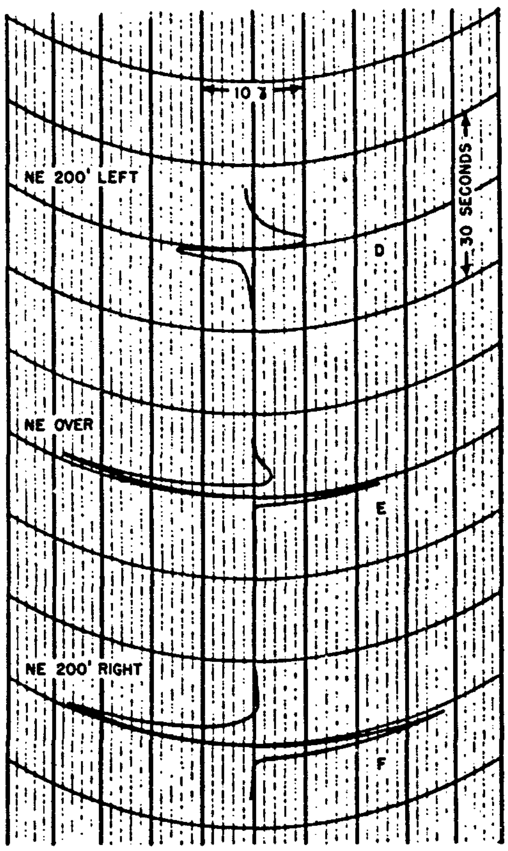


FIGURE 3. Signal resulting from crossing the contours of Figure 1 at 100 knots.

3. Let us now take up noise produced by local sources of magnetism. For convenience these may be broken into two classes: those sources which are part of the magnetometer and servo mechanism assembly, and those sources which are associated directly with the carrying aircraft. In the design and construction of the magnetometer head, that is, the servo motor and magnetometer array assembly, every care must be taken to insure that ferromagnetic materials are absent or at least sufficiently remote from the magnetometer assembly so as not to cause serious noise. There remains the transient magnetic field associated with eddy currents induced in nonferromagnetic conductors, which of necessity are in some cases very close to the magnetometer array, such as metallic parts of the gimbal system. These parts must be so designed as to avoid large sheets or closed loops which would permit flow of currents induced by motion in the earth's field. The procedure for dealing with sources of magnetism associated with the aircraft is discussed in Chapter 6.

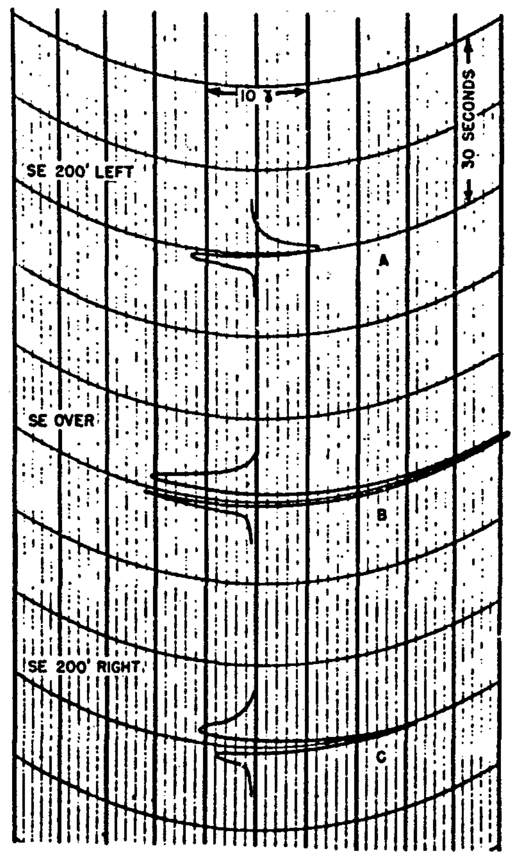


FIGURE 4. Signal resulting from crossing the contours of Figure 1 at 100 knots.

4. Noise generated in the core material itself is one of the more fundamental types of

noise and may be the ultimate limitation to the sensitivity of a saturable-core magnetometer. This has been discussed in Chapter 2.

5. Noise arising from the electronic part of the system, that is, vacuum tube microphonics,"

FIGURE 5. The DT-1/ASQ-1 polar magnetometer head and servo motor assembly used in the AN/ASQ-1.

fluctuations in the signals caused by erratic power supply voltages and similar phenomena, may be dealt with by conventional or semiconventional electronic engineering practice. In some cases special circuit details were incorporated in AN/ASQ-1, and in others drastic requirements in regard to production, inspection, and tube selection were imposed in order to minimize this source of noise. In the finished circuit, noise due to the detector, amplifier, and driver was measured as about 7 per cent of the total internal noise and was therefore negligible.

The principal design effort was directed toward the reduction of the classes of noise just discussed. There are, however, other considerations which limit the form which the system can take. Since the equipment must be airborne the usual limitations of size and weight apply. This was especially important for the AN/ASQ-1, since it was intended to install two complete systems in many aircraft for automatic bombing, as described in Chapter 4. In addition, on account of the need for dealing with noise arising from local sources of magnetism in the aircraft, restrictions are placed on the location of the magnetometer head. This condition imposes even more stringent limitations on the size and shape of this part of the system. Another condition is imposed by reason

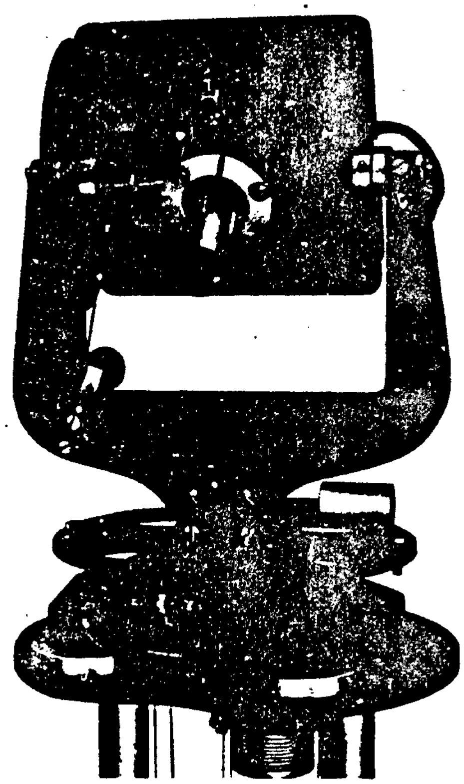


FIGURE 6. The DT-1/ASQ-1 polar magnetometer head used in AN/ASQ-1.

of the transient nature of the anomaly signal. It was early noticed that the effective signal-to-noise ratio was increased when a continuous record of the magnetometer indications was used. Since the anomaly signal was not repeti-

tive the memory feature of a continuous record greatly aids the observer's eye in distinguishing a small anomaly signal from spurious background fluctuations.

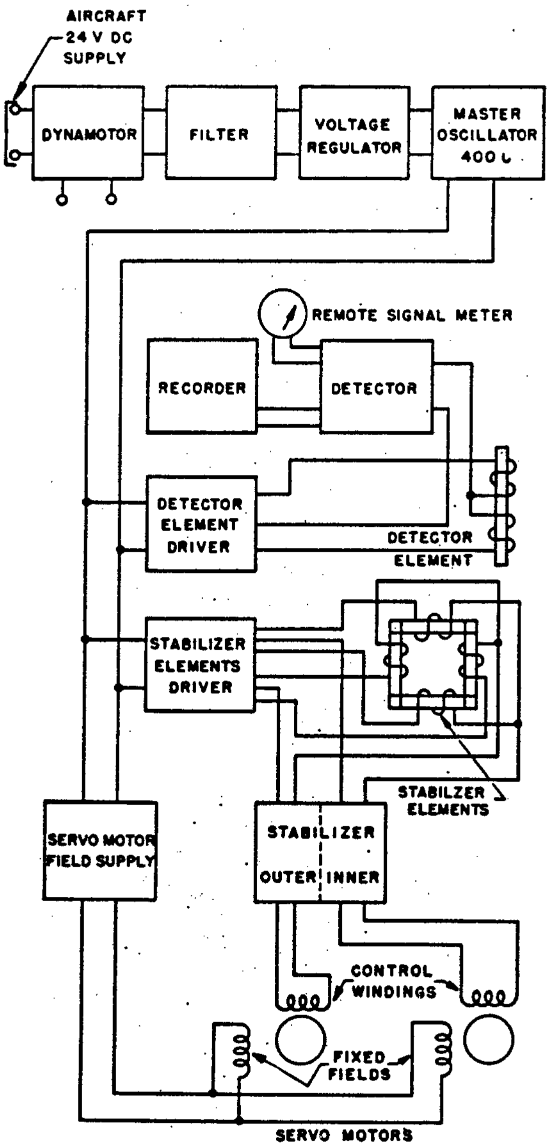


FIGURE 7. Schematic functional diagram of AN/ASQ-1.

The fundamental engineering design features utilized to meet the conditions laid down in the foregoing paragraphs are discussed in the next sections.

3.2 DESCRIPTION OF SYSTEM OPERATION

A photograph of the AN/ASQ-1[10, 11] equipment was shown in Figure 6 of Chapter 1. It occupies 3.9 cubic feet of space and has a normal installed weight of 135 pounds including installation accessories. Figure 5 shows the magnetometer and servo motor assembly removed from its housing. This assembly and housing were installed in various locations on different types of aircraft, as will be discussed in Chapter 6. Figure 6 is a close-up view of the square-head magnetometer assembly. This is the DT-1/ASQ-1, or "polar head." The arrangement of the three magnetometer pairs is as sketched in Figure 7 of Chapter 1.

A schematic functional diagram of the various parts of AN/ASQ-1 is given in Figure 7.

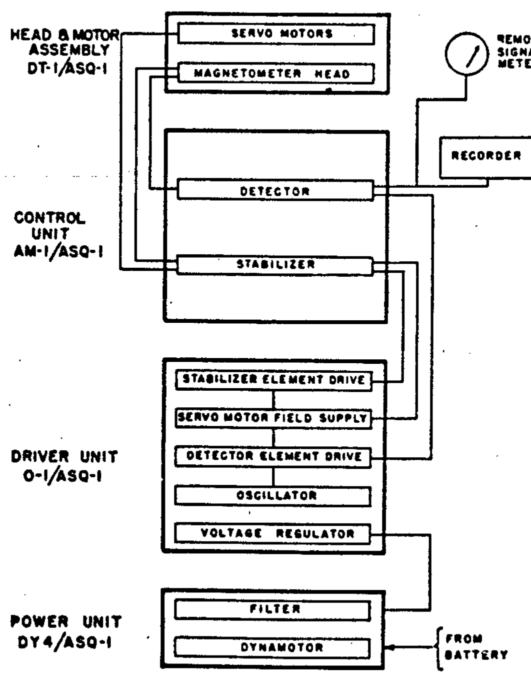


FIGURE 8. Location of AN/ASQ-1 circuit sections.

The fundamental power supply is the 24-volt d-c system of the aircraft, from which this equipment draws 8 to 12 amperes. This current operates a dynamotor producing about 550 volts direct current which, when passed

through a filter and an electronic voltage regulator, serves to operate a 400-cycle master oscillator. The 400-cycle voltage is fed to the detector circuit which will be described more fully in Section 3.4.2. If the spikes are of equal height the output of the amplifier is zero, but in the

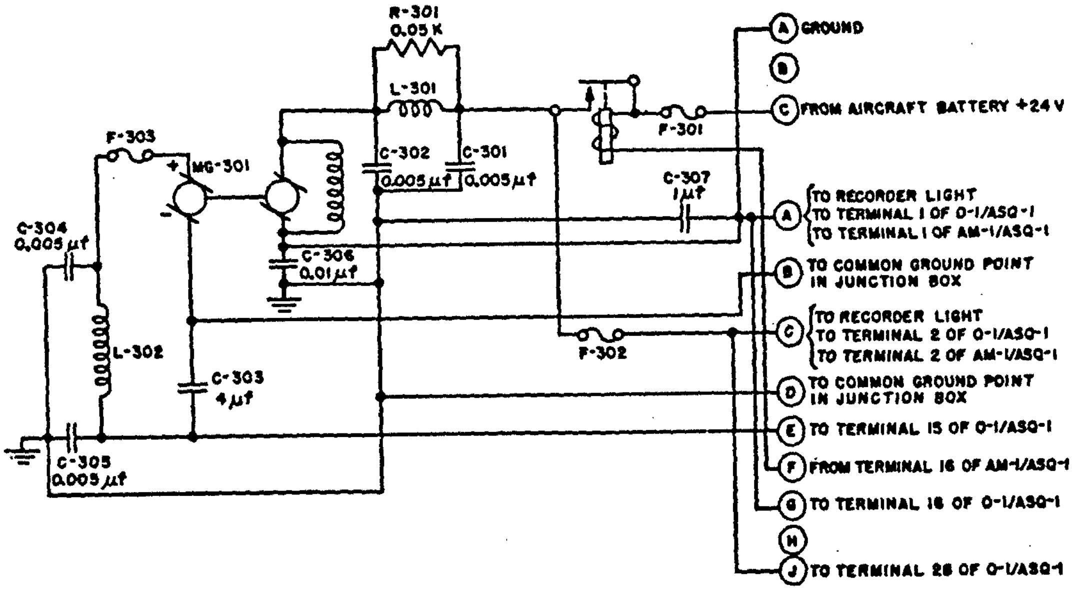


FIGURE 9. The DY-4/ASQ-1 dynamotor-filter power supply schematic circuit diagram.

and stabilizer magnetometer coils through appropriate driver circuits and also to the field windings of the servo motors.

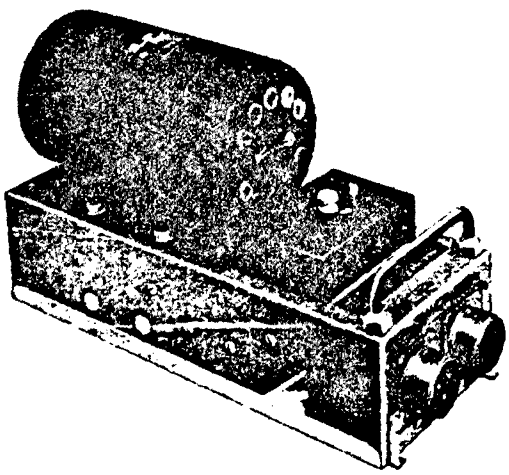


FIGURE 10. The DY-4/ASQ-1 dynamotor-filter power supply unit.

The spike pattern output of the detector element bridge goes to the detector-amplifier circuit

presence of a magnetic anomaly pattern, such as shown in Figure 9 of Chapter 2, a low-frequency transient voltage corresponding approximately to the envelope of the spikes is sent to the recording milliammeter. The recorder therefore traces an approximate graph of the time variation of magnetic field component parallel to the detector element. An auxiliary ammeter is also placed near the pilot's seat. The battery circuit which neutralizes the steady field of the earth is included in the detector amplifier in this diagram.

The outputs of the two stabilizer bridges go to the two stabilizer amplifier circuits. The way in which these control the servo motors has not yet been described. The system is as follows. The circuits are so arranged that in the absence of error-signal from the bridges they send 800-cycle voltage to the servo control windings. The field windings of these motors are continuously receiving 400-cycle voltage from the master oscillator. The 800 cycles on the control windings therefore produces no effect. However, as soon as a motion of the aircraft throws the magnetometer head out of

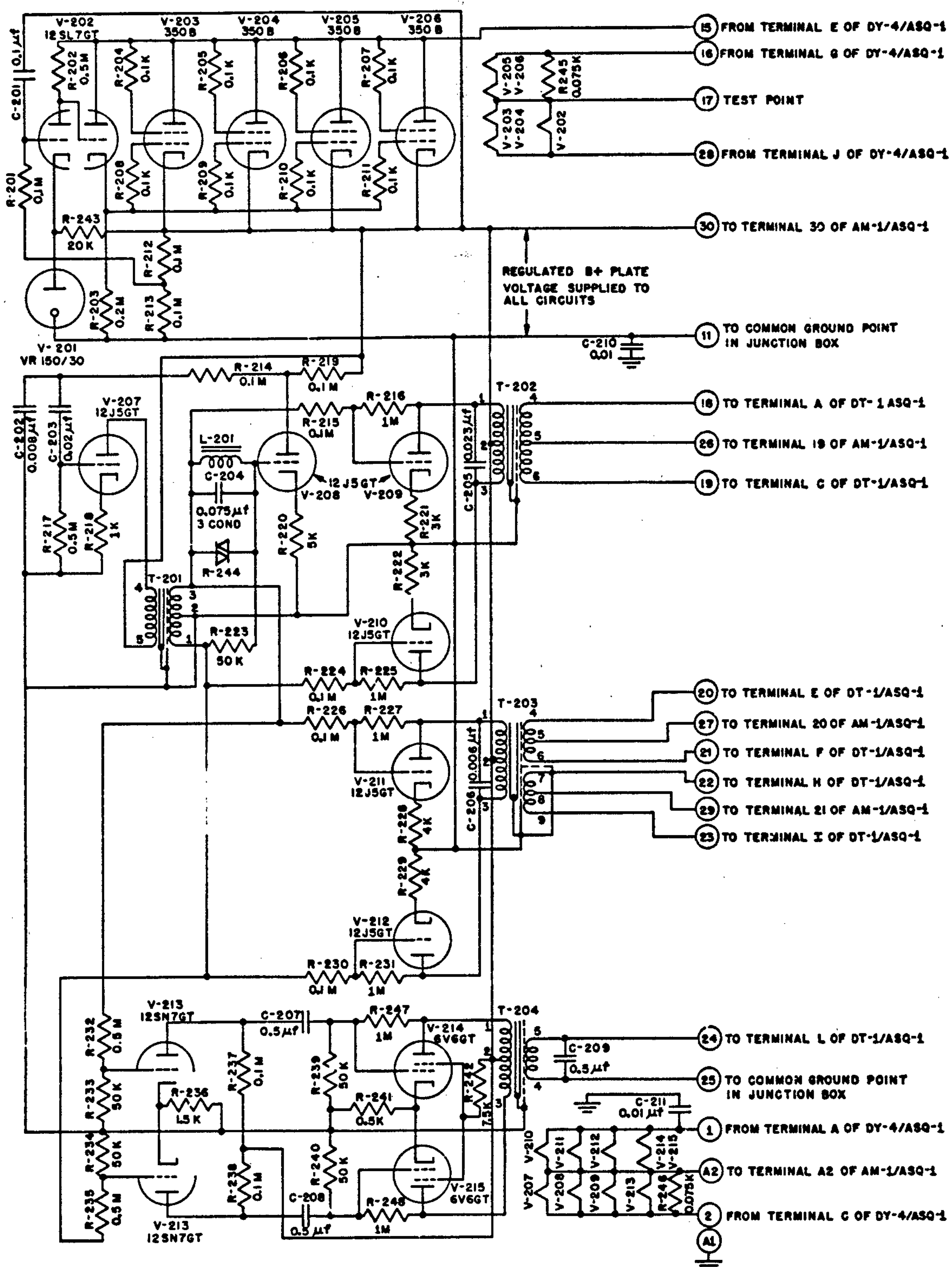


FIGURE 11. The 0-1/ASQ-1 driver unit, schematic circuit diagram. C204 must be adjusted to give a frequency of 400 c ±1. $B+$ to be adjusted to 300 v ±2% by selecting proper values of R212 and R213.

correct alignment, the stabilizer elements will experience field components parallel to their axes. The resulting changes in the spike pattern outputs of the bridges are translated by the

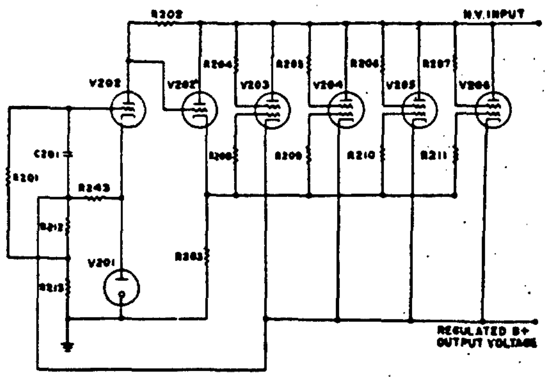


FIGURE 12. The electronic regulator circuit in 0-1/ASQ-1.

stabilizer amplifier circuits into 400-cycle voltages. Voltages of this frequency will cause the servo motors to rotate as long as they persist. The phases are properly adjusted to make the

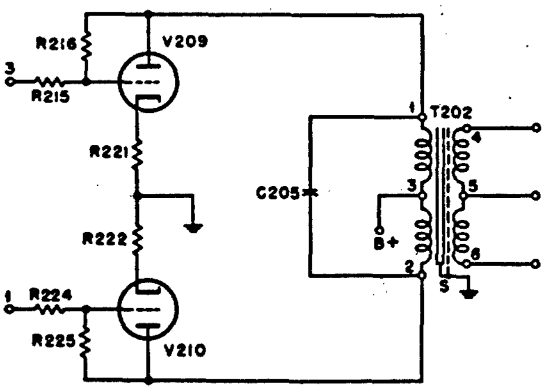


FIGURE 14. The detector driving amplifier circuit in 0-1/ASQ-1.

directions of the rotations such as to remove the error in magnetometer head alignment. As soon as the detector element is once more parallel to the field the stabilizer elements will be in the no-field position. The resulting pattern of spikes of equal height is translated again into 800-cycle voltage by the amplifier and the servos cease operating.

The stabilizer control circuit shown on the diagram includes the neutralizing circuits for correcting any lack of perpendicularity between detector and stabilizer elements on the head.

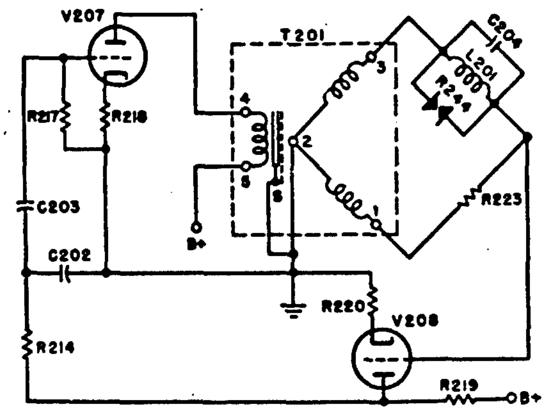


FIGURE 13. The 400-cycle oscillator circuit in 0-1/ASQ-1.

Figure 8 shows the location of the different circuits in the cabinet assemblies as manufactured. The next sections will take up the operation of these circuits one at a time.

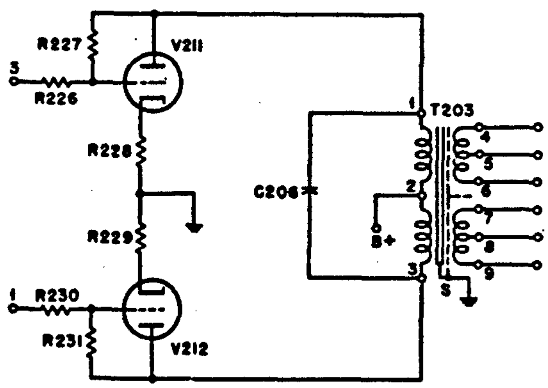


FIGURE 15. The orientor driving amplifier circuit in 0-1/ASQ-1.

3.3 THE POWER AND DRIVER CIRCUITS

3.3.1 The Power Unit, DY4/ASQ-1

The schematic diagram of the dynamotor-filter circuit is given in Figure 9, and a top view of the unit is shown in Figure 10. The

aircraft battery power is applied to the 5,200-rpm dynamotor MG301 through a power relay and a low-pass filter (L301, R301, C301, and C302). This filter prevents dynamotor brush noise from causing interference in the rest of the aircraft electrical system. The relay is actuated by the *Power* switch on the control unit

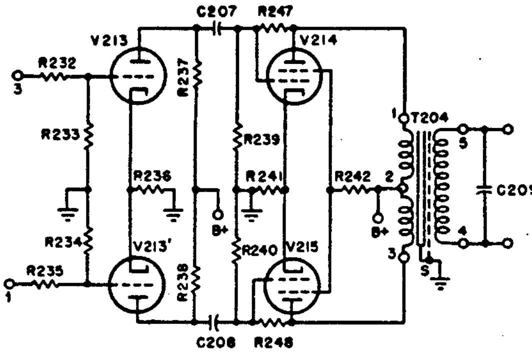


FIGURE 16. The constant servo motor field amplifier circuit in 0-1/ASQ-1.

panel. The high-voltage output of the dynamotor passes through an r-f filter (L302, C304, C305) before being sent on to the succeeding units of the system.

3.3.2 The Voltage Regulator

Figure 11 is the schematic circuit diagram of the O-1/ASQ-1 driver unit. This assembly includes the electronic voltage regulator, the 400-cycle master oscillator, the driver for the detecting magnetometer bridge, the drivers for the stabilizing magnetometer bridges, and the 400-cycle supply for the field windings of the two servo motors. Figure 12 is a detail of the regulator circuit alone.

If the dynamotor voltage increases, the current through the tube V201 becomes greater and the grid voltage for control tube V202 is increased. This results in a decrease in plate voltage on V202 which causes a decrease in the output of cathode follower V202′, thus lowering the grid voltage of the four regulator tubes, V203, V204, V205, and V206. The greater voltage drop across these tubes compensates for the increased input voltage. The system operates analogously to compensate for decreases in voltage. If the aircraft battery power supply varies over the range 20 to 30 volts the dynamotor output will vary between 450 and 720, but the regulated output will lie between 297.2 and 297.8 volts.

3.3.3 The 400-Cycle Oscillator

A detail of the 400-cycle oscillator circuit is shown in Figure 13. The oscillator consists of a two-stage amplifier, utilizing tubes V207 and V208. The tubes' output is fed back to the input in the proper phase to sustain oscillation through a coupling transformer T201 and a resonant bridge circuit. The center-tapped secondary winding of T201 comprises two arms of the bridge; iron-core inductor L201, mica capacitor C204, and Varistor R244 comprise the third, while wire-wound precision resistor R223 forms the fourth. The third arm is tuned

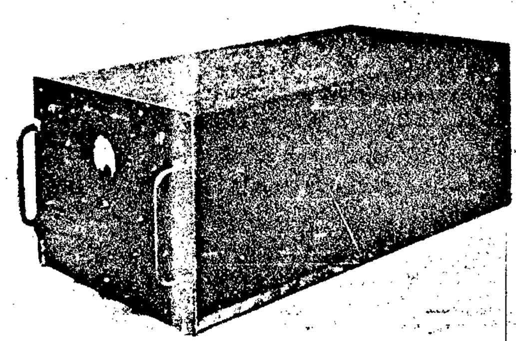


FIGURE 17. The AM-1/ASQ-1 control unit.

to give an output of 400c, although phase shifts in the feedback circuit cause the output frequency to differ slightly from the resonant frequency of the tank circuit.

The grid of tube V208 is driven by the potential which appears between the grounded center-tap of T201 and the junction of the third and fourth arms of the bridge. The amplitude of this driving voltage is determined by the ratio of the impedance of the resonant arm to the resistance of R223. The resistance of Varistor R244 varies inversely with the poten-

tial difference at its terminals. Its purpose is to regulate the voltage across the resonant arm of the bridge. Thus, if the voltage across T201 should rise because of increased output from V208 and thus decrease the voltage across T201. If the filament-to-plate voltages applied to tubes V207 and V208 should decrease, the Varistor would operate in the opposite direc-

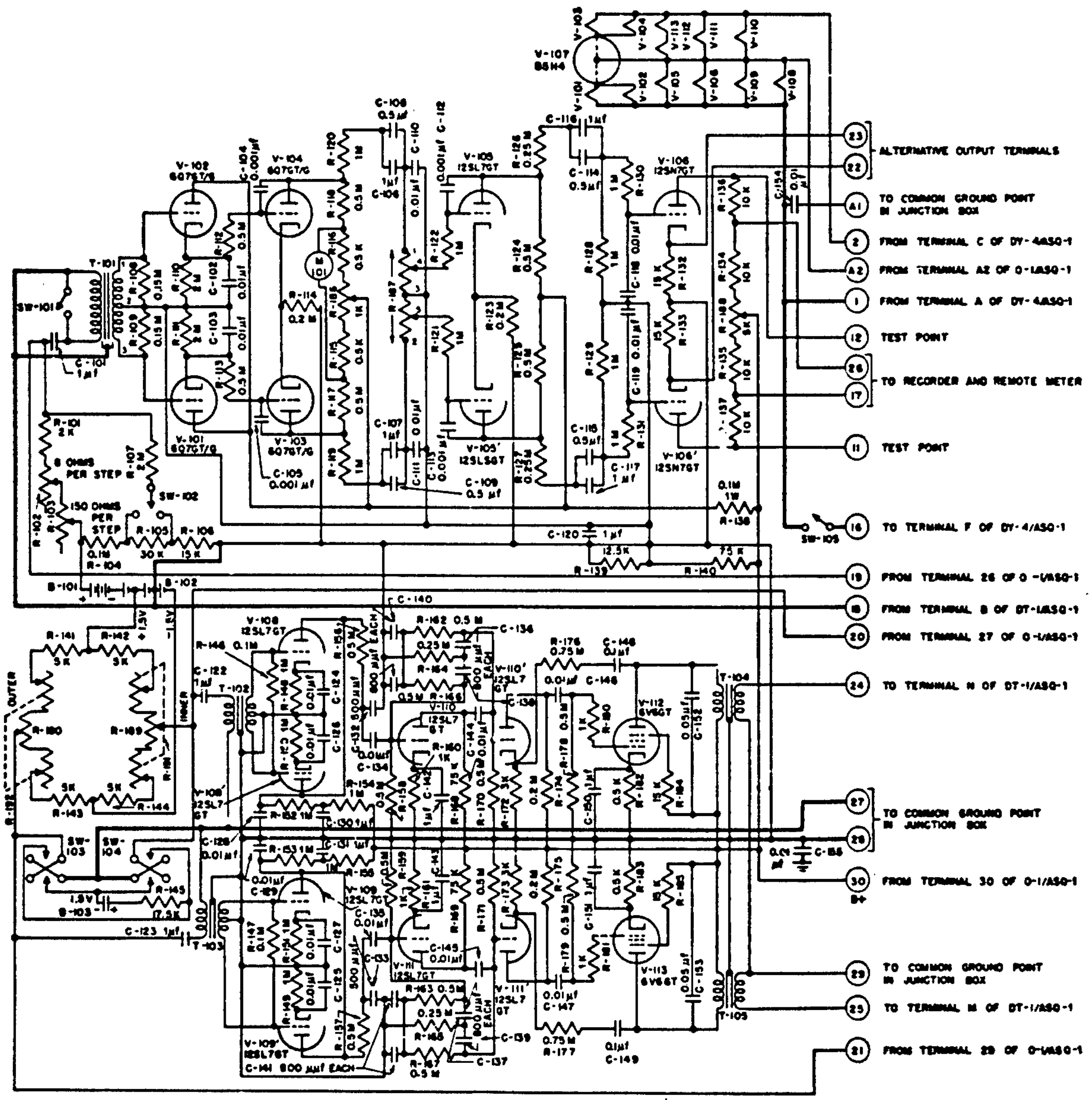


FIGURE 18. AM-1/ASQ-1 unit, schematic circuit diagram.

tubes V207 and V208 resulting from increased filament or plate voltage, the resistance of R244 would decrease and further shunt the circuit of L201 and C204. This would reduce the amplitude of the drive voltage to the grid of tion. Thus the amplitude of the oscillator output voltage, tapped off of points 1 and 3 across the T201 secondary for use in the later circuits, is maintained very nearly constant.

Cathode resistors R218 and R220 of tubes

V207 and V208 are not by-passed. The resulting degeneration tends to relieve the requirement for nonmicrophonic tubes and further reduces the effect on the oscillator output of variations in filament voltage. The filter network, consisting of R214 and C202, is for the purpose of suppressing parasitic oscillations.

3.3.4 The Magnetometer Driving Amplifiers and the Motor Field Amplifier

The output of the oscillator is applied to three separate amplifier channels, the secondary winding of transformer T201 providing push-

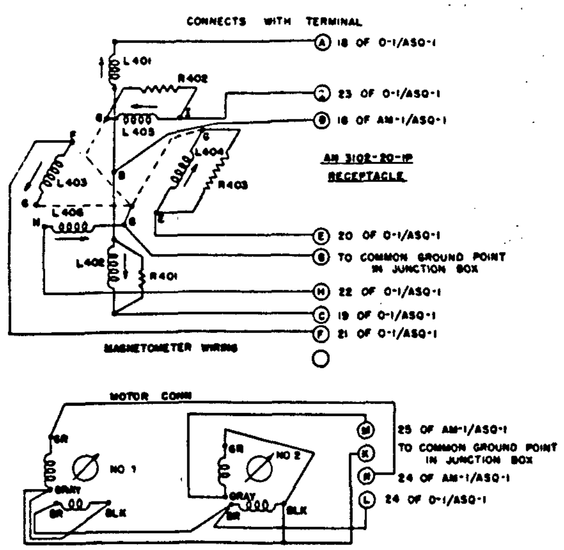


FIGURE 19. DT-1/ASQ-1 unit, schematic circuit diagram.

pull drive for all three, as shown by Figures 14, 15, and 16.

The detector-magnetometer elements are driven by the amplifier channel with tubes V209 and V210; the orientor elements, by the amplifier with tubes V211 and V212; and the constant fields of the motors are energized by the amplifier with tubes V213, V213′, V214, and V215. The input grids of all three channels are connected to terminals 1 and 3 of transformer T201 through resistors which serve for isolation. The plates of all the amplifier tubes except V213 and V213′ are connected to their respective grids through 1-megohm resistors to provide voltage degeneration. This effect reduces the microphonic and d-c voltage variations and the harmonic distortion.

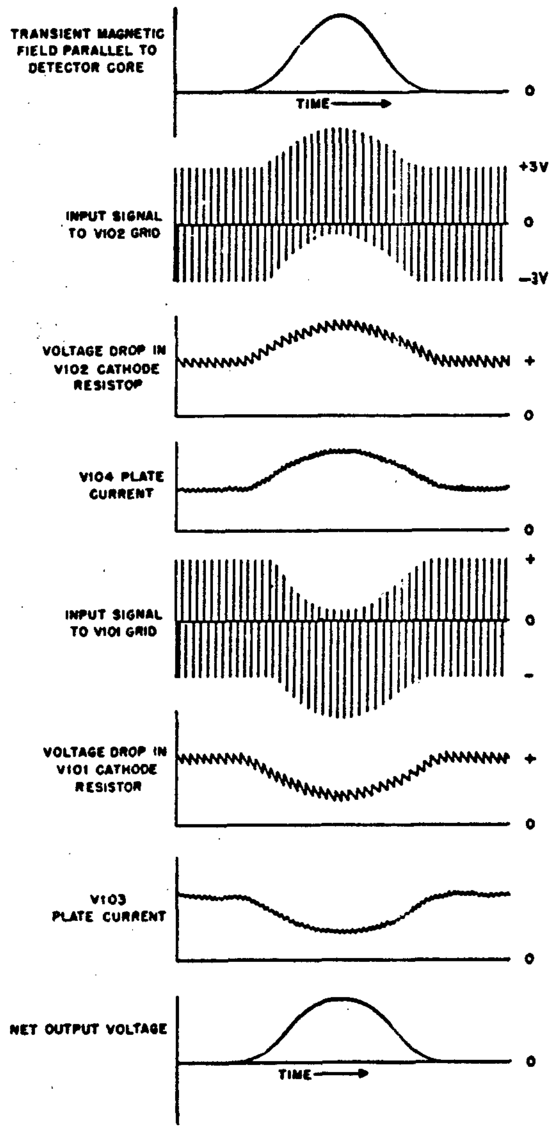


FIGURE 20. Schematic graphs of voltage and current variations within the detector amplifier circuit (not to scale).

Capacitor C205 is connected across the primary winding of transformer T202 to reduce distortion by tuning the output of the detector-driver amplifier channel to 400 c. Similarly, capacitor C206 is across the primary

winding of output transformer T203 of the orientor-driver to improve the wave form and bring the phase angle between the outputs of the orientor and motor field channels to zero.

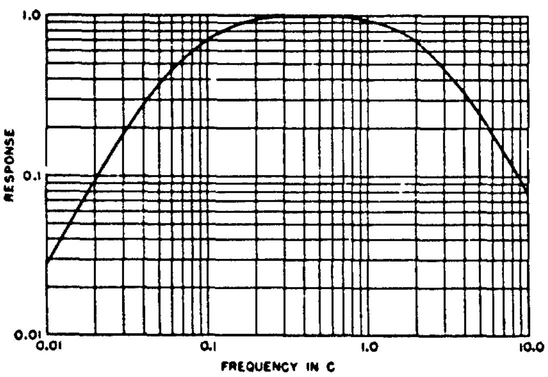


FIGURE 21. Response-frequency characteristic of AN/ASQ-1 exclusive of recorder.

In the motor field amplifier circuit, capacitor C209 is connected across the secondary of transformer T204. The capacitor is chosen to obtain maximum output. This occurs when its combination with the transformer winding and the constant field windings of the servo motors has a resonant frequency of 400 c.

3.1 THE DETECTOR CIRCUITS

The amplifier for the detector bridge output and the battery circuit for neutralizing the constant effect of the earth's field are contained in the chassis labeled AM-1/ASQ-1 shown in Figure 17. This chassis also contains the orienting magnetometer circuits to be described in Section 3.5. The schematic diagram is given in Figure 18. The wiring of the magnetometer head and servo motor assembly is shown by Figure 19.

3.1.1 The Magnetic Neutralizing Circuit

The 4.5-volt dry cells B101 and B102 send current in the same direction through both coils of the detecting magnetometer so as to cause a field throughout the Permalloy strip equal and opposite to the constant field of the earth. (The field due to the 400-cycle driving current is oppositely directed in the two halves of the strip, so as to cause the detecting effect as previously described.) The rheostats R102 and R103 which control this neutralizing current appear on either side of the meter in Figure 17.

Switch SW102, in the bottom center of the control panel, is a test switch. Closing it in either direction causes a small change in the neutralizing current and provides the so-called click test. The change in current has the same effect on the detector element as a change in

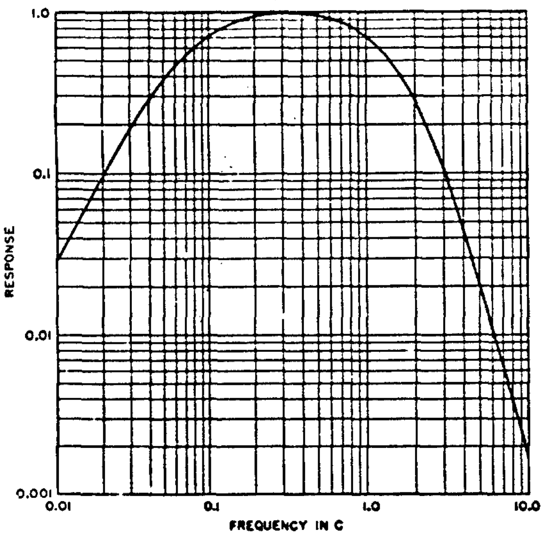


FIGURE 22. Response-frequency characteristic of AN/ASQ-1, including recorder.

the earth's field. The click test shows whether or not the equipment is operating properly and also gives a rough check on its sensitivity.[12]

3.1.2 The Detector Amplifier Circuit

The upper half of Figure 18 is the diagram of the signal amplifier. Figure 20 indicates the general nature of the signal response at several points in the circuit.

THE AMPLIFICATION PRINCIPLE

The voltage between terminals 1 and 2 on the secondary of T101 will repeat the spike pattern of the magnetometer bridge output.

V102 will pass current (passing most on the positive spikes of the grid signal) until the charge in C102 builds up sufficiently to maintain an *average negative grid bias* of about 50 volts. The condenser does not discharge completely between pulses because the time constant of the circuit C102-R110 is large compared to the pulse period. The voltage across R110 traces a sawtooth curve of about 1 volt "tooth-

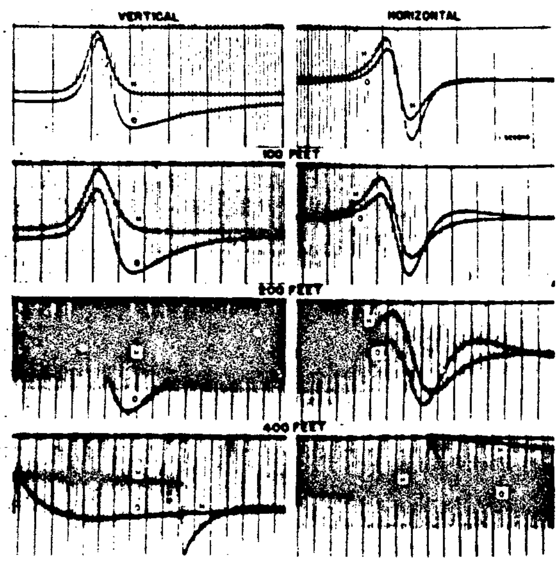


FIGURE 23. Response of AN/ASQ-1 without recorder, to various magnetic signals of submarine type and to a discontinuous change in magnetic field.

height." When a magnetic anomaly signal causes the positive spikes to increase and the negative ones to decrease, the result is an increase in the average current through the tube. The average voltage drop across R110 increases as shown in Figure 20.

The potential of the V104 grid therefore rises; this tube then passes more current and a greater drop across its plate resistor results. This lowers the potential of contact 4 on R187 and so decreases the current through V105. The resulting rise in the latter's plate voltage raises the grid potential of V106, increases the V106 plate current, and so lowers the potential of the point between R134 and R136 which constitutes one terminal of the output.

The independent companion channel, containing tubes V101, V103, V105′, and V106′, is likewise a four-stage RC-coupled amplifier. Since V101 is connected in the opposite direction across T101 as compared to V102, a magnetometer bridge spike which decreases the grid bias of V101 increases that of V102 and vice versa. A similar opposition in polarity continues throughout this amplifier, with the result that the potential of the output point between R137 and R135 rises at the time the potential of the upper channel output point falls. The recording milliammeter and remote signal meter which are connected in series between these two points receive by this mechanism an amplified voltage pulse of approximately the same shape as the magnetic signal.

Circuit Details

Any inequality in amplification between the first two stages of the upper channel and the first two stages of the lower channel may be balanced out by a slight alteration of the plate voltages of V103 and V104. This is done by shorting the driver pulses with switch SW101 and then adjusting the screwdriver control of rheostat R186 until the microammeter M101

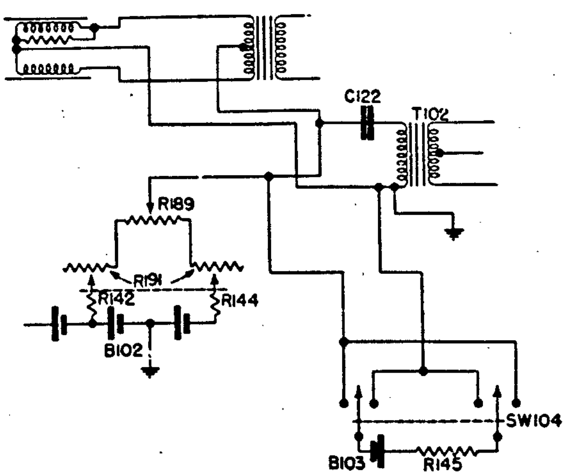


FIGURE 24. Orientor biasing circuit in AM-1/ASQ-1.

reads zero. A similar opportunity for balancing the circuit as a whole is given by adjustable rheostat R188 at the output end.

The amplification of the circuit may be varied

by means of the dual potentiometer R187 located in the center of the control panel. A change in the position of its two sliders—coupled together and moving oppositely—alters the fraction of the V103 and V104 plate voltage submarine signals. The lowest frequencies, principally caused by magnetic fluctuations within the aircraft, are blocked by the condensers in series, such as C106. High-frequency transients are shorted out by the condensers

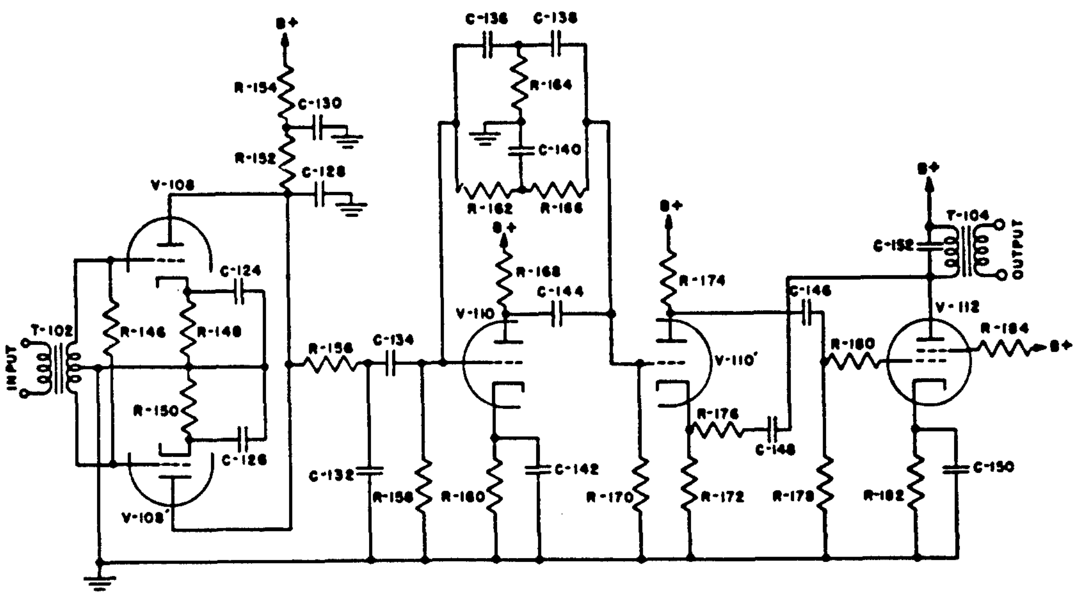


FIGURE 25. Inner orienting amplifier circuit in AM-1/ASQ-1.

variation which is passed on to the V105 and V105′ grids.

The four similar filter networks (C106, C108, C110, ½ R187), (C114, C116, C118, R128, in parallel, such as C110. Figure 21 gives the frequency response of the amplifier alone and Figure 22 shows the effect of including the mechanical recorder. Figure 23 is a series of

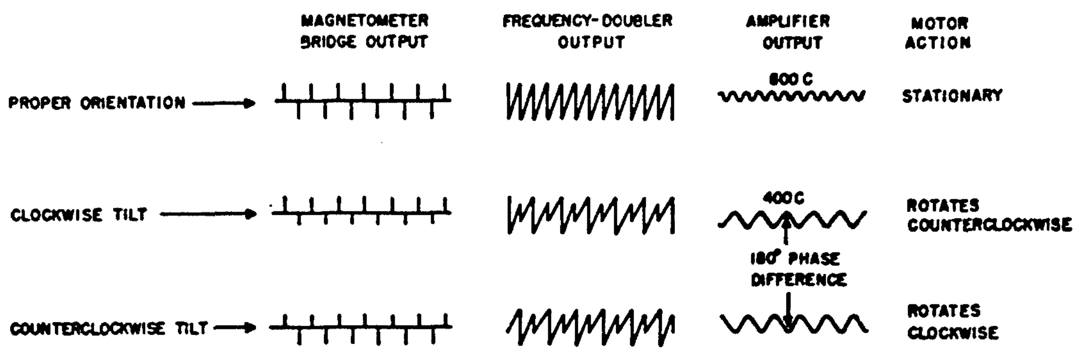


FIGURE 26. Illustrating directional control of stabilizers.

R130), (C107, C109, C111, ½ R187), and (C115, C117, C119, R129, R131) determine the frequency response of the system—placing the pass band in the range occupied by the usual oscillograms showing the output voltage of AN/ASQ-1, without recorder, in response to some magnetic signal of typical submarine type and also to a discontinuous change in magnetic

field.[13] Resistors R119, R120, R126, and R127 are added to provide the proper plate loads for their respective tubes.

The feedback condensers C104, C105, C112, and C113 help to lower the gain for high-fre-

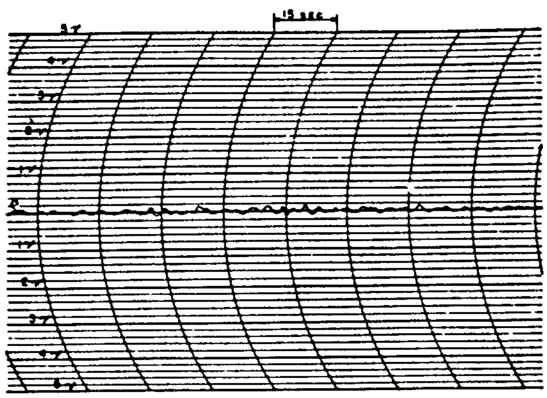


FIGURE 27. Test record made under magnetically quiet conditions.

quency signals. The feedback currents flow through the adjoining grid resistors and produce voltage drops in opposition to the input voltages, an effect which becomes larger at higher frequencies.

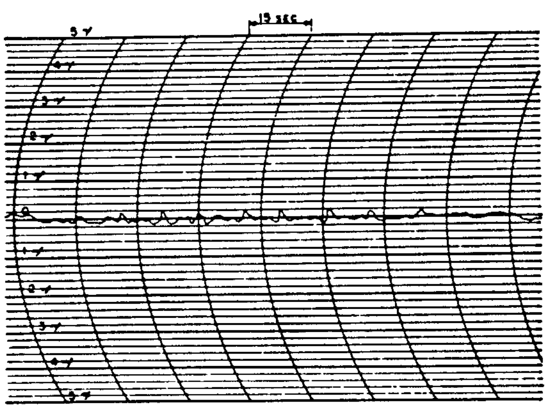


FIGURE 29. Background of magnetic noise recorded during straight and level flight of a G-21A airplane.

The last three stages have large cathode resistors to increase their stability. In order not to leave the grids too strongly negative because of the cathode resistor drops, the constant positive voltage across R139 is added to the grid bias of each of these stages.

The cathodes of tubes V106 and V106′ are tied together by a jumper across their cathode resistors. This jumper may be removed to per-

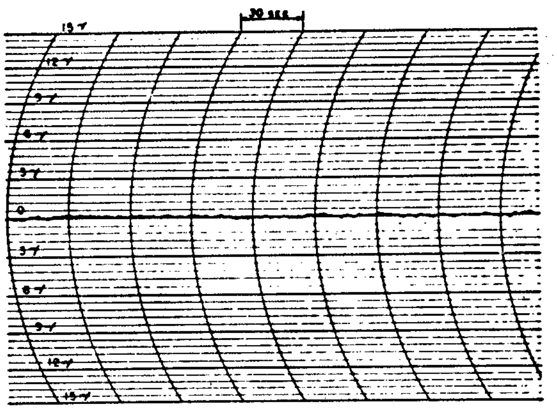


FIGURE 28. Background of magnetic noise recorded during straight and level flight of a PBY airplane.

mit use of the cathode circuit as a low-impedance output circuit. Tube V107 is a voltage regulator for stabilizing the filament supply to the critical first two stages.

V101 and V102 are operated in the plate current cutoff region. They must have uniform characteristics, and it is essential for high amplification that the cutoff be sharp. Therefore the tubes used in these sockets require special testing and selection on a special tube tester designed to check these critical characteristics.[14]

The recorder is a standard Esterline-Angus type AW 0.5-0-0.5 recording milliammeter, with a chart speed of $1\frac{1}{2}$ inch per minute, revised to include a lighting system in the case.

3.5 THE ORIENTOR CIRCUITS

The lower half of Figure 18 shows the battery circuit for electrically aligning the orienting magnetometers so that they will maintain the detector strictly parallel to the field, and it also gives the circuits by means of which the orienting magnetometers control the servo motors.

3.3.1 The Magnetometer Alignment Circuits

Resistors R142, R144, R189 and the two halves of R191 are connected in series as a potentiometer across battery B102. R191 and R189 constitute coarse and fine adjustments for sending a small neutralizing current in either direction through the inner magnetometer bridge. (The orientors are labeled as inner or outer from the location of their respective gimbals.) Figure 24 is a detail of the connections.

Test switch SW104, with B103 and R145, increases or decreases the neutralizing current slightly and so provides a means of testing for parallelism between the detector and the ambient field. A small change in the neutralizing current causes the magnetometer assembly to rotate to a new position. As a result of the change, the detector produces an output signal on the recorder. An exactly equal change in the original neutralizing current is made in the opposite direction, and a detector signal is again obtained. These two signals will be of equal amplitude only if the detector element was initially parallel to the field and was thus deoriented by the same amount in each direction. If the neutralizing current is adjusted so that these test signals are equal, the element assembly is then at the proper position so far as rotation about the axis of this orientor is concerned.

An identical circuit adjusts and tests the neutralization of the outer orientor bridge.

3.3.2 The Orienting Amplifier Circuits

That part of Figure 18 which includes the amplifier circuit for the inner orientor is repeated in Figure 25. The spike pattern from the magnetometer bridge is applied through T102 to the grids of V108 and V108′ which are connected as a *frequency doubler*. V108 conducts on alternate spikes and is biased almost to cutoff on the intervening ones by the drop across C124 and R148, similar to the action of V102 in the detector amplifier. V108′ passes those spikes which V108 does not. Figure 26 shows the time variation of the V108-V108′ plate potential. Since there is one pulse for every spike the output of this stage will show 800 pulses per second. If the magnetometer head is properly oriented the pulses will be of equal height, but if there is misorientation

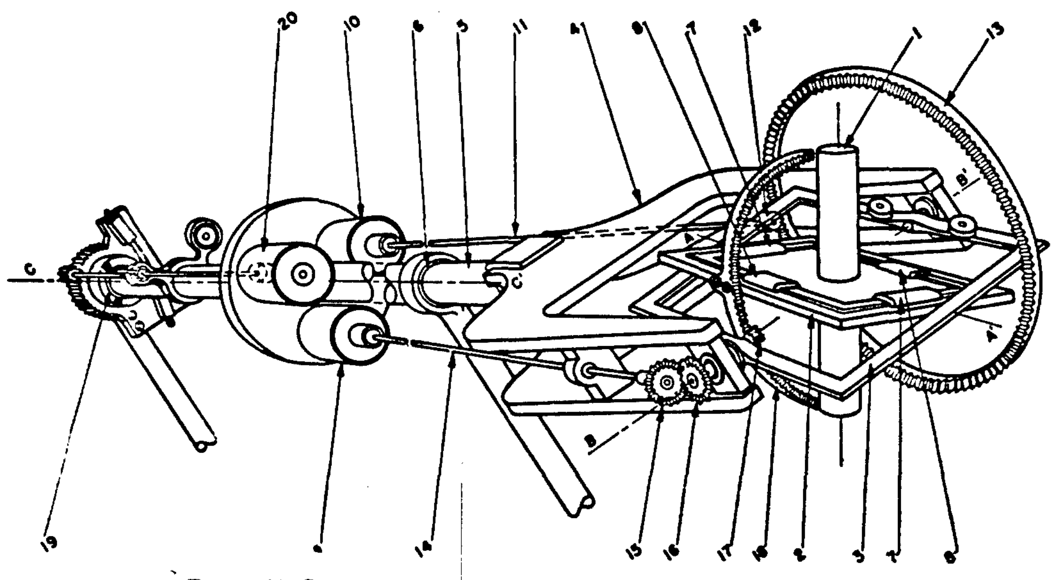


FIGURE 30. Schematic diagrams of the universal magnetometer head.

alternate pulses will be smaller and the pattern will contain a 400-cycle component.

The purpose of the remainder of the circuit is to filter, shape, and amplify this 400-cycle component whenever it exists. The frequency doubler output is sent to the grid of V110 through the filter R156, C132, C134, R158. This tube is a tuned inverse feedback stage. The plate output of V110 is fed back (through R166, C138, C136, R162, R164, and C140) to the grid in proper phase to *oppose* the input signal for all frequencies except 400 cycles. The latter frequency is not passed by the filter. The result is to weaken all the signal except the 400-cycle component. The next two stages, V110′ and V112, constitute a feedback amplifier whose purpose is to amplify the 400-cycle component and bring the output closer to a sinusoidal shape. As indicated in Figure 26 the phase of the output and direction of rotation of the servo will depend on whether V108 or V108′ passes the larger pulses. The outer orienting magnetometers are served by an identical system, companion to the one just described.

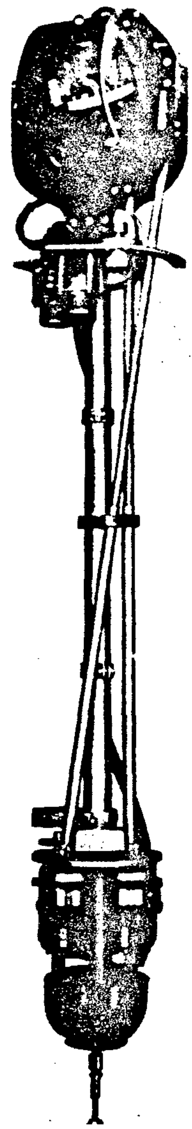


FIGURE 31. DT-3/ASQ-1 universal head, with streamlined housing removed.

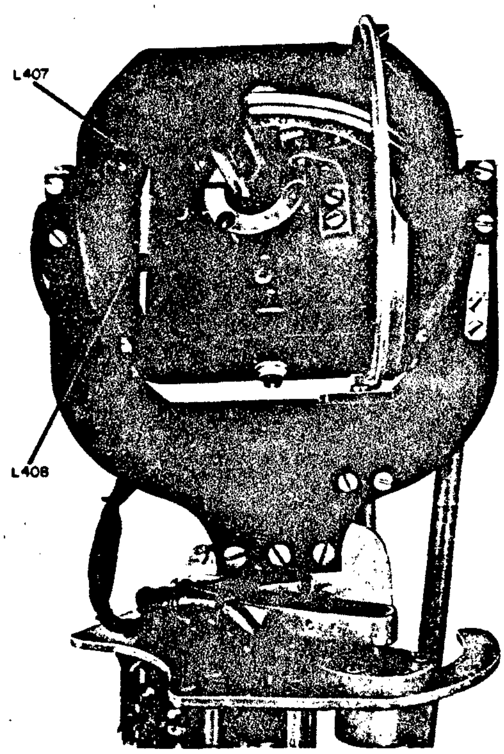


FIGURE 32. DT-3/ASQ-1 magnetometer head assembly.

Circuit Details. C152 increases the output by being tuned to resonate at 400 cycles with T104 and the servo winding. R180 serves to suppress spurious oscillations in the output stage. Just as in the detector circuit, V108-V108′ must be

a tube carefully selected for balance. C128 and C130 help to make the V108-V108′ plate voltage pulse into a broader "sawtooth"—closer to the desired sine wave than the narrow spike pattern. When either tube conducts, these condensers partially discharge and so hold the plate potential relatively low for some time after the spike has passed. The condenser charge (and so the plate voltage) must be gradually rebuilt after each spike by B+ supply current through R154 and R152.

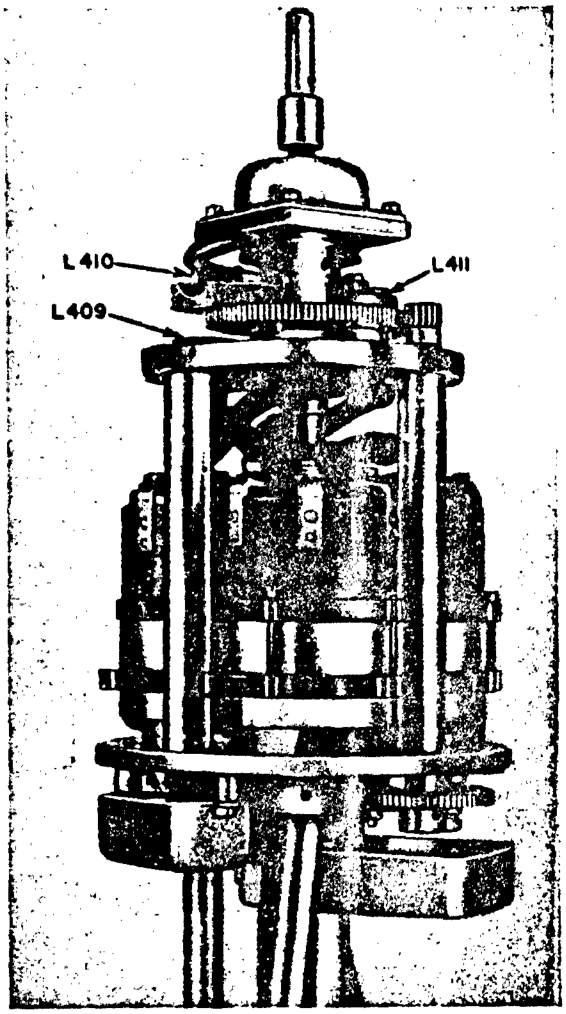


FIGURE 33. DT-3/ASQ-1 motor assembly showing proportional control system coil.

The cathode bias elements C154-R148 and C126-R150 are very important in determining the dynamic response of the orienting system. In the steady state V108 and V108′ are so strongly biased that only the tops of the grid voltage peaks cause current flow. If a sudden shift of the magnetometer takes place, the input peaks will instantly become unbalanced. Due to the long time constant of the bias elements the average biases will not reach their new steady values until several peaks have occurred. During this time the 400-cycle component of the output will be larger than normal, and greater restoring torque on the magnetometer head will result than would otherwise be obtained. This tends to speed up the mechanical response of the system.

As the head reapproaches the normal orientation the peaks approach balance faster than the average bias, resulting in reversal of phase of the servo motor voltage and, therefore, in the production of a *back torque* which stops the system at the normal position and prevents overshooting. Such a "rate circuit" therefore acts as an anti-hunt device.

This completes the discussion of the AN/ASQ-1 circuits.

3.6 PERFORMANCE CHARACTERISTICS OF AN/ASQ-1[15]

Sensitivity of Detector

The sensitivity of the detector system is adjustable by steps over a wide range. At the lowest value, a sinusoidal magnetic signal at 0.3 c must have an amplitude of 125 gammas to produce a full-scale deflection on the recorder. At the highest sensitivity and the same frequency, a signal of one gamma will produce a full-scale deflection. The sensitivity normally used is intermediate and the choice in a particular case will depend upon the magnetic noise produced by the aircraft and by the variations in the earth's field. The available range is more than adequate, because the signal received from a submarine will rarely exceed 100 gammas and submarine signals smaller than one gamma will probably not be recognizable because of the background noise.

Noise Levels

The inherent background noise is shown in

Figure 27. At least part of this output is caused by time variations of the earth's magnetic field.

Figure 28 shows the background noise recorded by AN/ASQ-1 equipment during straight and level flight of a PBY airplane. On the chart, time is shown as progressing from left to right, with the interval between lines representing 30 seconds. The maximum amplitude during the interval shown is about 0.25 gamma, so that a submarine signal of one or two gammas would be detectable. Figure 29 shows the noise recorded by the same equipment during straight and level flight of a Grumman G21-A airplane. The maximum amplitude in this case is also less than 0.25 gamma. The noise recorded during rapid maneuvers may be considerably larger, depending the uncompensated magnetic fields of the particular aircraft.

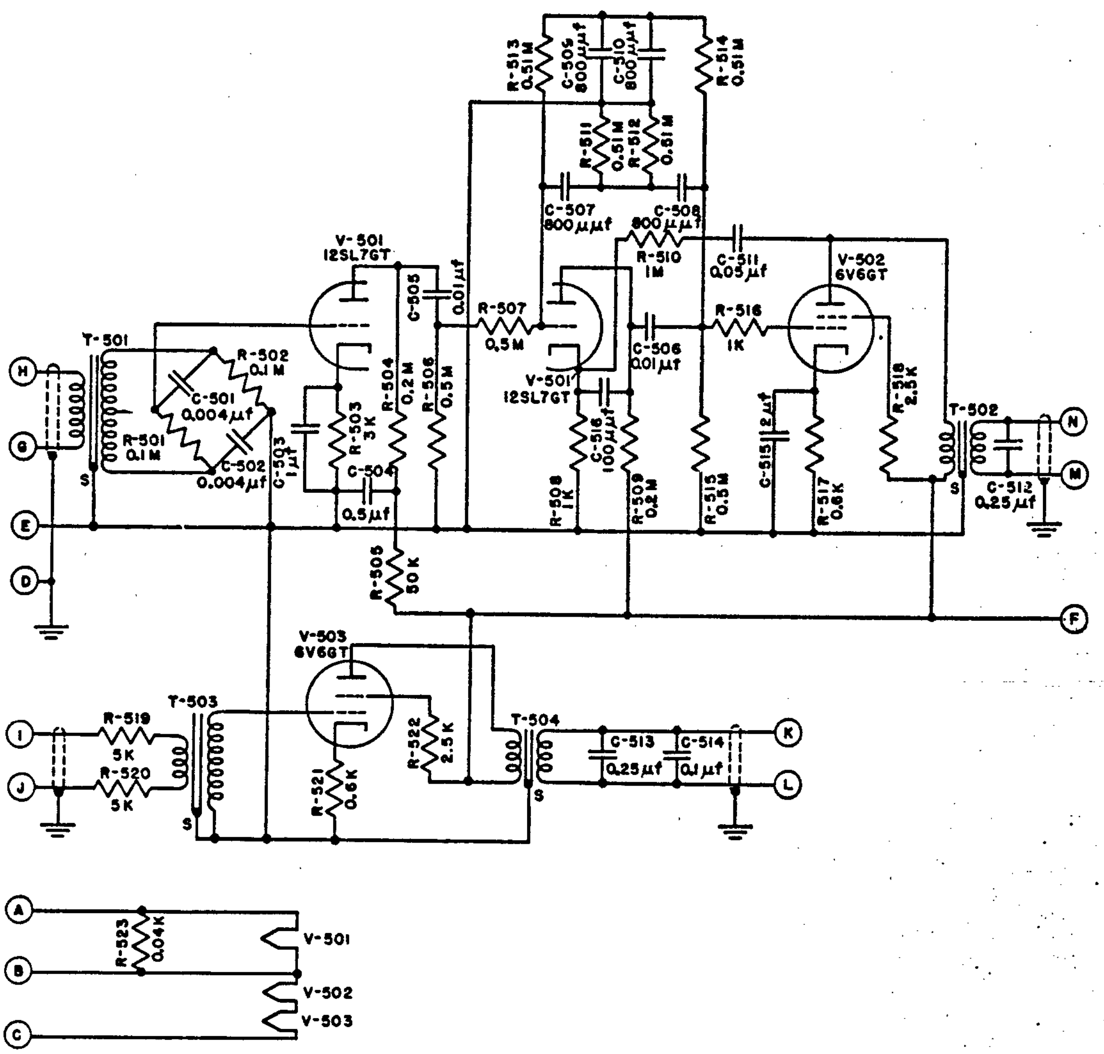


FIGURE 34. AM-9/ASQ-1A unit, schematic circuit diagram.

PRECISION OF STABILIZATION

The overall performance of the AN/ASQ-1 equipment is closely related to the precision with which the stabilizer system keeps the detector element oriented in the earth's magnetic field. The maximum stabilizer error of AN/

ASQ-1 during usual aircraft maneuvers is only about five minutes of arc. The magnetic noise recorded during aircraft maneuvers, which arises from magnetization and eddy currents, will establish a higher threshold of noise than can be attributed to the orientor errors.

Adjustments in Flight

The deviation of the magnetic state of the detector from perfect magnetic balance is indicated continuously by the balance meter on the panel of the control unit. Since this deviation depends on the magnitude of the earth's field, readjustment will be necessary if the aircraft travels to a new area where the earth's field has a markedly different value. Howeve., if a decrease of 20 per cent in sensitivity is allowable, then an increase or decrease of 1,000 gammas in the earth's field can occur before readjustment is necessary.

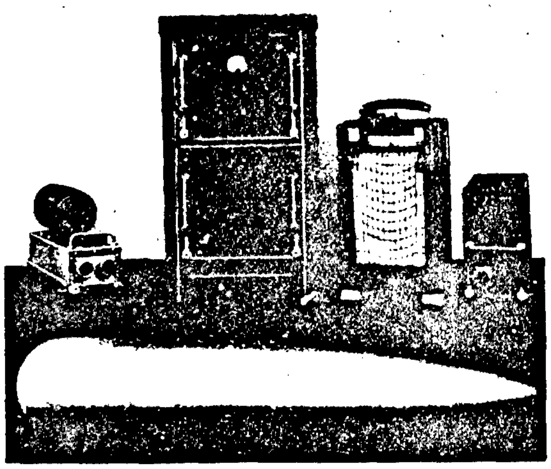


Figure 35. AN/ASQ-1A equipment.

The need for readjustment of the stabilizer system neutralization circuit arises only because of the drift of circuit constants with time. Under reasonable conditions of operation the adjustment of orientation will be required about twice a day.[16]

Serviceability

Reliability of operation is a most important consideration in the design and manufacture of equipment to be used under conditions of varying supply voltage, variable temperature, severe vibrations, and high humidity. The AN/ASQ-1 operates equally well with supply voltages from 22 to 29 volts, and the output is practically unaffected by sudden changes of supply voltage within this range.

The equipment is designed and tested for operation at temperatures between —20 and 140 F. The only effect of large temperature variations within this range is a small change in detector sensitivity. This is not a serious defect since the sensitivity is readily adjustable by means of the control previously described. Before being assembled, circuit components are selected, processed, and tested for stability under varying temperatures.

The most stringent requirements on design and construction are imposed by the severe vibration under which the equipment is used. It is accordingly made mechanically rugged and provided with antishock mountings. The

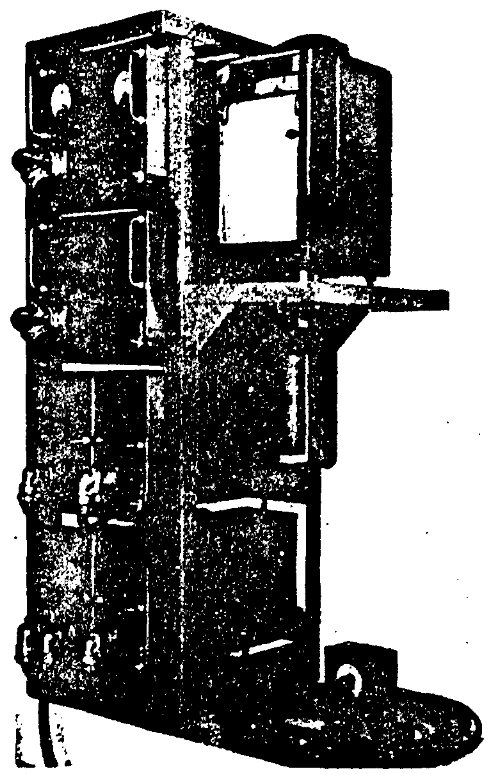


Figure 36. Mark IV B-2 magnetic airborne detection circuits and recorder.

electronic circuits are designed for low microphonic effects. Each unit is tested for satisfactory operation while subjected to violent vibration on a shaking table.[17]

Consideration has been given to the problem of operation under conditions of high humidity. Long-term stability and reliability have been achieved through the use of high-quality components, careful choice of insulating materials, and thorough impregnation of parts with moistureproof materials.

3.7 THE AN/ASQ-1A SYSTEM, WITH UNIVERSAL HEAD

The AN/ASQ-1 system so far considered used the DT-1/ASQ-1 magnetometer head assembly which permitted rotation about two axes. This is satisfactory in the polar and middle latitudes, but in the equatorial regions where the magnetic dip angle is less than $\pm 20°$ serious trouble results. To counteract certain heading changes and angles of bank of the plane, the gimbals are required to rotate at speeds much greater than the drive motors can provide. The gimbals may also lock in a dead-center position.[20] Changes in the method of mounting[21,22] the two-axis head will overcome this trouble, but these permit a winding up

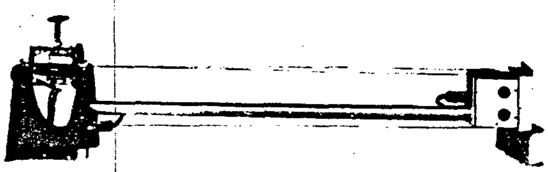


FIGURE 37. Mark IV B-2 magnetometer head assembly.

and eventual breaking of the electrical leads as the airplane executes 360° turns.

The difficulty was solved in the DT-3/ASQ-1 head,[18,19] the so-called universal head, by adding a third axis of rotation. MAD systems incorporating this head are labeled AN/ASQ-1A. The essential mechanical parts of a universal head are shown in Figure 30. The detector element (1) is mounted rigidly through the orientor plate (2), which is pivoted in the closed gimbal (3). This pair of pivot bearings forms one axis AA', and the bearing positions of the closed gimbal frame form another axis BB' at right angles to it. These bearings on the closed gimbal are set in the open-fork gimbal (4). The center of the fork forms with suspending shaft (5) the third (slow-follow) axis, CC'. This shaft is supported by a bearing (6) which is fixed to the airplane so as to hold axis CC' parallel to the line of flight.

By means of electronic equipment previously described the stabilizer elements (7, 8) on the

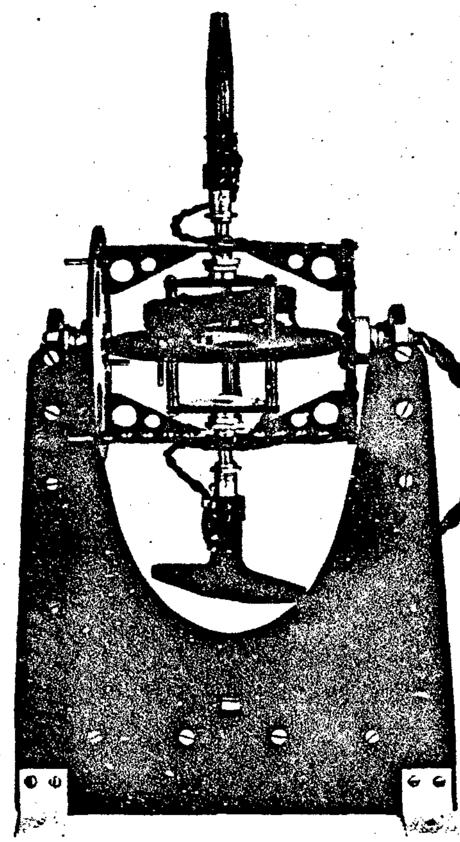


FIGURE 38. Mark IV B-2 magnetometer head.

orientor plate control two motors (9, 10). Motor (10) effects stabilization about the second axis by means of shaft (14), pinion (12), and gear (13). Motor (9) does the same about the first axis, with shaft (14), bevel gears (15, 16), pinion (17), and gear (18).

All the parts mentioned are mounted directly or indirectly on shaft (5) and rotate with this shaft about the third axis, through bearing (6) and a similar bearing (19) near the motor end. This rotation is the slow-follow motion, and motor (20), rigidly attached to the outer bearing structure, provides stabilization of the slow-follow axis.

One simple type of difficulty of the two-axis mounting may be understood from this drawing. Suppose the assembly to be installed with axis *BB′ fixed* parallel to the line of flight of the plane, as is usual with DT-1/ASQ-1. Then for level flight *BB′* would be horizontal. At the magnetic equator the detector should lie in the horizontal plane for level flight, which means that the orientor plate (2) should lie in the vertical plane. But with *BB′* fixed any vertical alignment of plate (2) places the detector pointing parallel to *BB′*. No other azimuths in the horizontal plane would be accessible to the detector. The MAD system could only function correctly when the airplane was heading due north. If the system were installed with *BB′* fixed in a vertical position the detector would continuously rotate perpendicular to *BB′* as the aircraft executed a spiral search pattern in level flight, and the leads would be broken. Provision for rotation about the third axis *CC′* whenever necessary removes the difficulty.

Figure 31 shows the DT-3/ASQ-1 assembly with its streamlined housing removed. Figure 32 is a view of the head proper. The discussion of complicated cases involving various bank, pitch-heading angles of the plane in locations of varying dip angle can best be carried out mathematically[23-25] or with a movable model. The results show that to serve its purpose the motion about the *CC′* axis must introduce a bank of the instrument to counteract partially any bank of the plane. The motion can be as slow as the turn of the plane and does need to be very precise.

To accomplish this, rotations about *CC′* are made to accompany and be proportional to any rotations about *AA′* caused by the servos in response to aircraft maneuvers. Coils L407 and L408 in Figure 32 pick up stray field from the detector element. The voltage induced in them depends upon the angle between the detector element and the outer frame and so is responsive to rotations about *AA′*. Figure 33 shows coils L410 and L411 which are carried by the support frame and so are fixed in position with the aircraft. These coils are fed 400-cycle current from the detector element driver. Coil L409 is fastened to the rotating members. The voltage induced in it at any instant will depend upon its angular position with respect to L410 and L411, and so this voltage will be responsive to any rotation of the head assembly about axis *CC′*.

The voltage from L407 and L408 is now fed into an auxiliary amplifier (labeled AM-9/ASQ-1A) in series opposition to the voltage from L409. Now any rotation about *AA′* caused by the fast servo in response to aircraft maneuver will create a voltage unbalance in this amplifier which will actuate motor (20). This motor will cause a slow rotation about *CC′* until the resulting voltage change in L409 counterbalances the original voltage change in L407-L408 and so removes the driving force.

The universal head obviates the difficulties mentioned for all operating conditions except with bank angles of over 40° near the magnetic equator. This latter restriction is not serious.

Figure 34 is the schematic circuit diagram of the AM-9/ASQ-1A amplifier. The V503 stage amplifies the constant 400-cycle voltage from the detector element driver entering at *I, J* in order to energize the field of the servo motor. Stages using tubes V501, V501′, and V502 amplify any 400-cycle voltage fed in at *H, G* from the coil combination (L407 + L408 — L409) and send it to the other windings of the motor.

The complete AN/ASQ-1A equipment is shown in Figure 35. In its finished state it represents considerable improvement in ruggedness and reduction of weight over the older model Mark IV B-2 which is shown in Figures 36 to 38.

Chapter 4

MAD SIGNAL STUDIES

As development work continued and MAD equipment reached the Armed Services, the need grew for more exact information about field strength variations. It was evident that the use of an actual submarine and aircraft was not practicable.[1] In addition to the difficulties in scheduling and carrying out such trials, the wide range of magnetic dip angle and state of submarine magnetization encountered in combat could not readily be simulated.

The MAD signal is determined by a number of variable factors, including the distance from the target submarine, the path of the aircraft, nature of the submarine's field, and the response of the electronic circuit. The characteristics of the submarine's field depend upon its magnetic history, which determines its permanent magnetic moment, and its location and direction at the time of contact, which determine its induced moment and the resultant field pattern. Table 1 lists a few of the submarine moments measured in various circumstances during the war.[2, 3]

Table 1. Some submarine moments measured under various circumstances. All values are in units 10^7 times a cgs unit.

Submarine	Approximate total moment	Longitudinal component	Transverse component	Vertical component
S-44	23			
USS 178	10.3			
R-16	3			
USS 258	10			
USS 253	7.6			
USS 167	5			
USS 282	26			
British "T" Class	14			
USS 172	14			
German U-boat	24			
R boat	1			
USS 204	5			
German U-boat	17			
German U-boat	5	4	4	1
German U-boat	5	0	−1	−3
German U-boat	10-20	10 × cosine of heading angle	2 × sine of heading angle	5

Because of the wide range of variables which must be investigated, the use of models seemed a suitable approach to the problem. It is possible to reproduce with great exactness the phenomena associated with the magnetic objects with models, if the relative physical dimensions and distribution of magnetism in the object are carefully reproduced at the reduced scale. The model studies here described provided a foundation for the design of the automatic trippers and the dual automatic AN/ASQ-2 system taken up in Chapter 5. They also indicated directions for the improvement of operating tactics in the field.

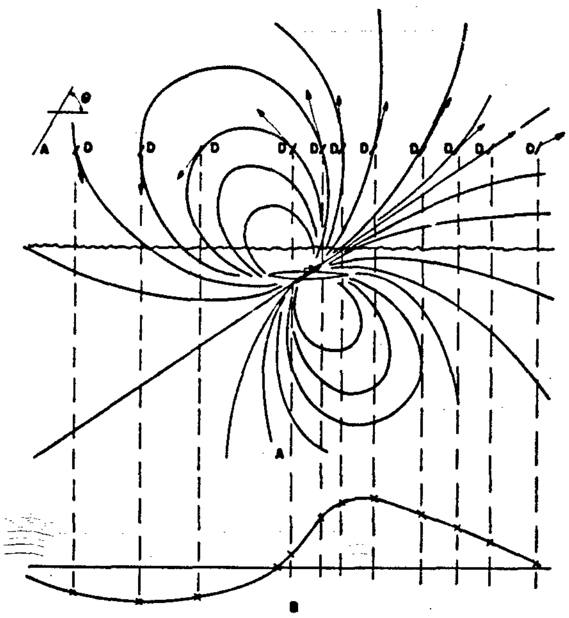


Figure 1. A. Vertical cross section through a typical submarine field. The short lines at the positions D represent various successive positions at the detecting magnetometer element. They all make the same angle θ with the horizontal. B. MAD signal received by aircraft passing directly over submarine.

Two classes of investigation were carried out. In the *static contour studies* the anomaly field above various submarine models was mapped and statistical conclusions were drawn

on various features, such as the most frequently occurring positions of maximum field strength. In the *dynamic signal studies* the submarine

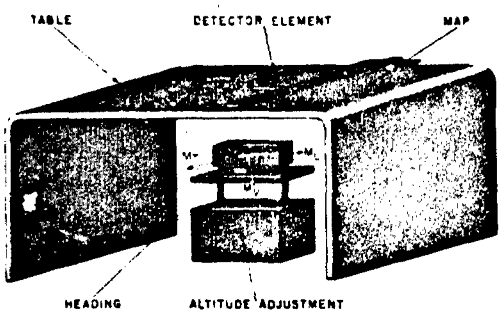
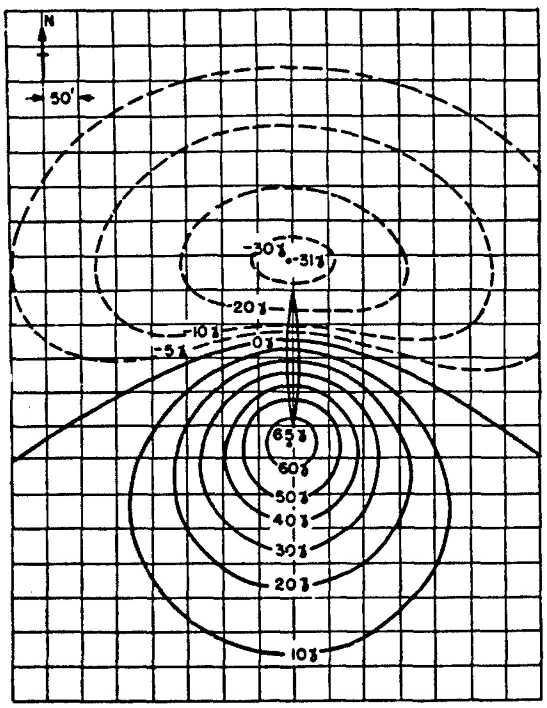


FIGURE 2. Arrangement for plotting static contour maps.



$M_V = 5 \times 10^7$ cgs $M_L = 1 \times 10^6$ cgs
$M_T = 0$ $h = 200'$
Angle of dip = 60°

FIGURE 3. Contour chart of submarine at a large dip angle, heading N.

model was moved past a standard AN/ASQ-1 detector (or vice versa) at various speeds and orientations which might occur in combat. The resulting recorder traces were studied statistically and in detail.

4.1 STATIC CONTOUR STUDIES

4.1.1 Equipment

The magnetometer head may be simulated in the model by using a detector with a fixed orientation determined by the prevailing magnetic field in the location to be investigated. Reproduction of the orienting system is not

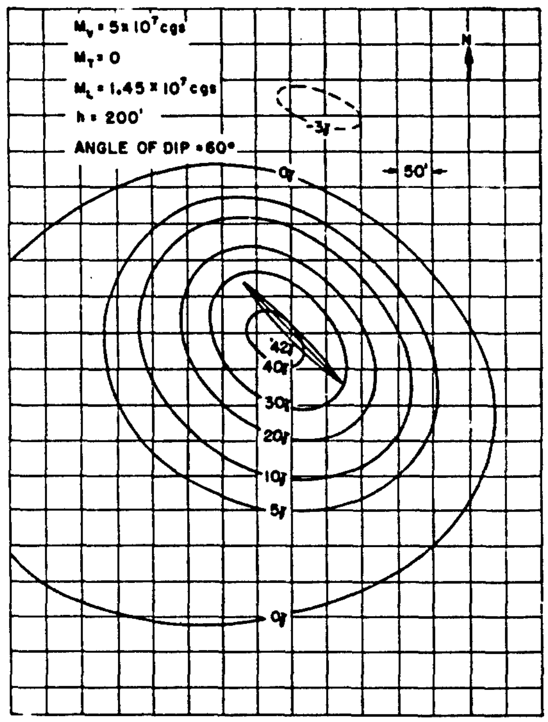


FIGURE 4. Contour chart of submarine at a large dip angle, heading SE.

necessary. The actual magnitude of the magnetic moment associated with a submarine need not necessarily be reduced by the same scaling factor as the physical dimensions. An appropriate reduction may be chosen to suit the circuit constants of apparatus associated with the model. Having chosen an arbitrary value of magnetization convenient for use with associated equipment, one must then calculate a scaling factor which indicates the relationship

between the magnetic moment of the actual object and that of the scale model. This calculation can be simplified in the case of a submarine by considering the magnetic moment to be that of a concentrated dipole. It has been shown that, at distances comparable to or greater than the length of a submarine, the

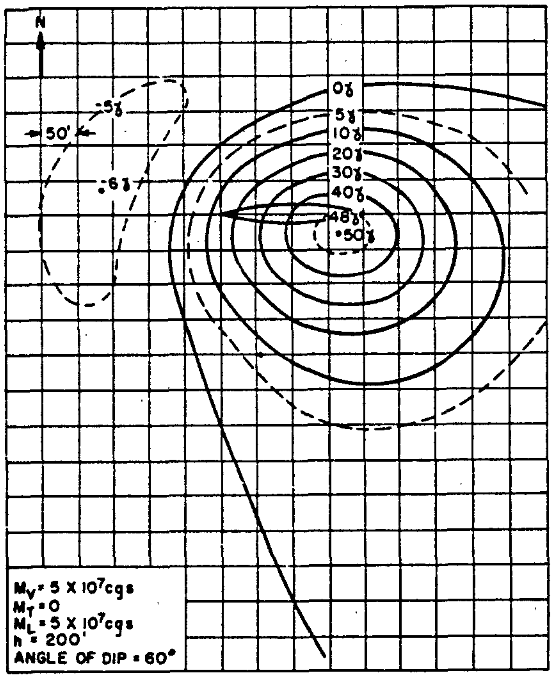


FIGURE 5. Contour chart of submarine at a large dip angle, heading W.

field due to the distributed magnetism of the submarine differs from that due to a dipole of like total moment by small amounts, the difference being of the order of 7 per cent when the separation is the same as the length of the submarine and decreasing as the separation is increased. Thus, if a greater separation is chosen, quite accurate calculations may be made using dipole equations. Figure 1A shows a vertical section through a typical submarine dipole field.

If the system comprising submarine and detector is reduced to a size convenient for reproduction in a laboratory, several problems at once present themselves. In the first place, the change in field to be measured is of the same order as the differences in field intensity which abound in the average electrical laboratory. In addition, investigation is limited to the single magnetic latitude at which the laboratory is located. The problems can be overcome if the earth's field can be neglected and only the field due to the submarine model measured. The effect of the earth's field may be eliminated by simulating the field of the submarine in the model by means of an alternating field of a given frequency, with magnitude and direction adjustable at will, and making the detector sensitive only to alternating fields of that frequency. Since such a detector is sensitive only to the single frequency alternating field, it is unaf-

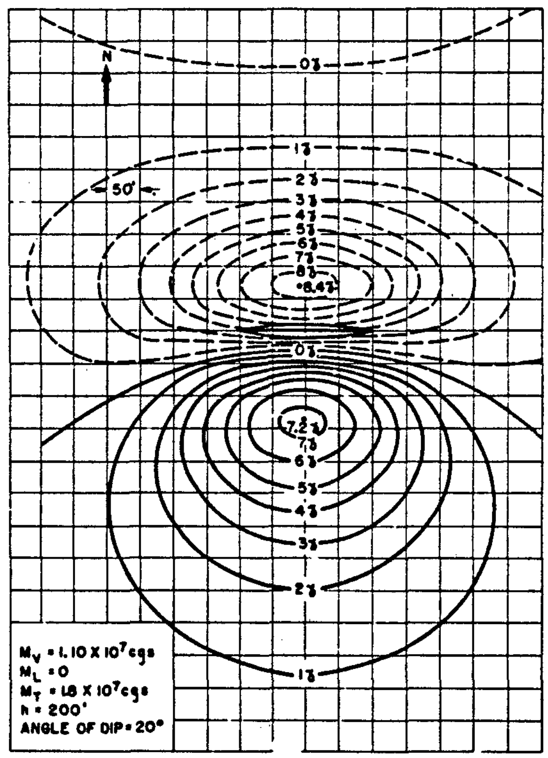


FIGURE 6. Contour chart of submarine at low dip angle, heading E. (Dashed contours represent negative γ values.)

fected by the earth's steady magnetic field and the magnetic gradients of the laboratory. Investigations can be carried out for any magnetic latitude since only the magnetization of the submarine and the relative orientation of the detector element and the field of the submarine need be varied in order to simulate operation at various latitudes.

The total moment associated with the submarine may be conveniently represented by means of three component moments which add vectorially to give a resultant of the proper magnitude and in the proper direction. The components may be chosen in such manner that one of them lies along the fore and aft or longitudinal axis of the submarine, a second along the vertical axis of the submarine, and a third along the athwartship or transverse axis of the submarine. These components may be designated as the longitudinal, vertical, and transverse moments, their positive directions being taken as toward the bow, down, and toward port, respectively. The three component moments may be generated in three mutually perpendicular coils so oriented in space that the moments lie along the chosen axes of the submarine. If these coils are excited with direct current or properly phased alternating current, a field, the direction and magnitude of which will be determined by the magnitude of the excitation of the three coils, will be generated. It can be shown that in the case of alternating current excitation the polarity or direction of the component moments of the submarine may be reproduced in the model by appropriately shifting the relative phases of the excitations. Direction or polarity may then be determined through the use of a reference signal, with respect to which the relative phases of the excitation signals may be measured. If such excitation is used, the output of the pickup coil will be an alternating voltage, the rms magnitude

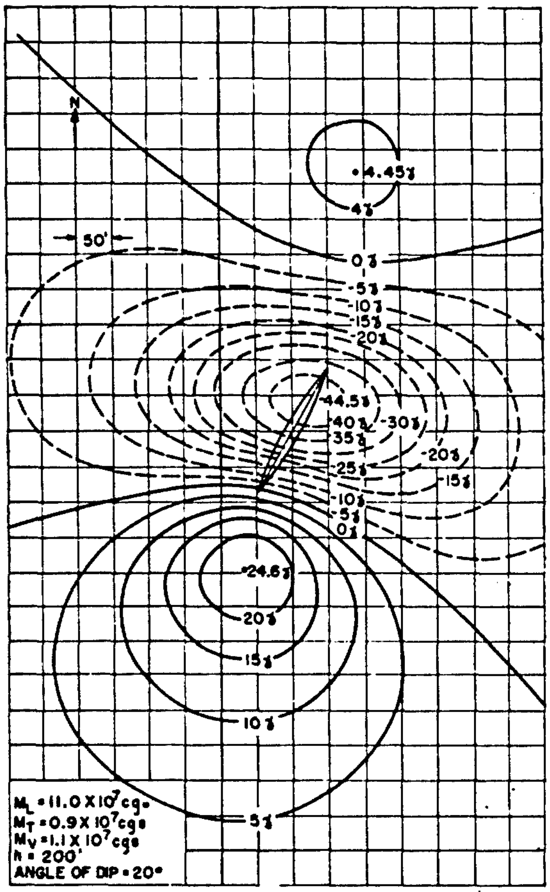


FIGURE 7. Contour chart of submarine at low dip angle and 30° heading.

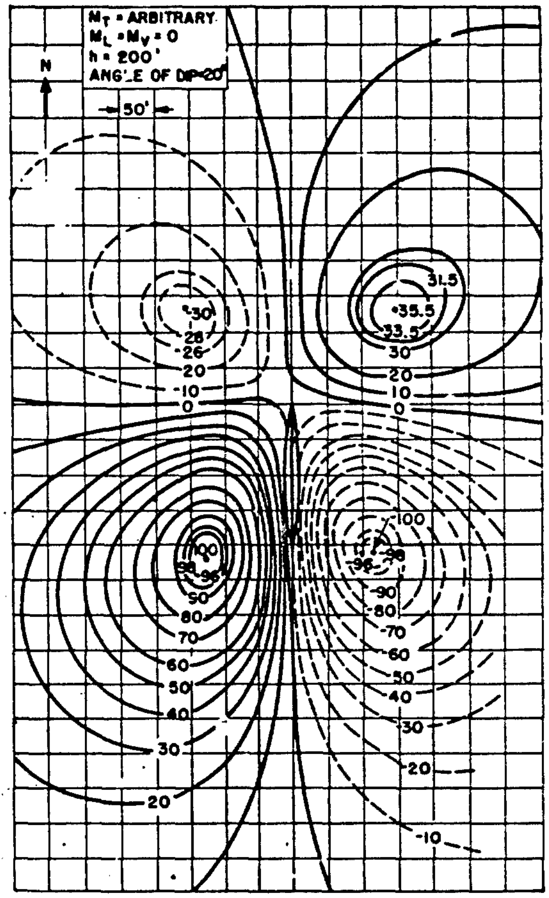


FIGURE 8. Contour chart of submarine at low dip angle, heading N or S.

of which may be measured by a vacuum tube voltmeter.

A magnetic plotting table utilizing the principles above discussed was constructed,[4] using throughout a scale of 1 centimeter to 10 feet. As shown schematically in Figure 2, the apparatus comprises a drafting table, beneath which is mounted the model submarine and to the surface of which a suitable charting paper table top is taken to represent a chosen altitude surface and adjustments in the height of the elevator simulate changes not only in the altitude of the airplane bearing the detection equipment but also in the submersion of the submarine. The 500-cycle excitation for the three coils is provided by means of a single oscillator, a separate amplifier being provided for each of the three coils. The pickup coil is

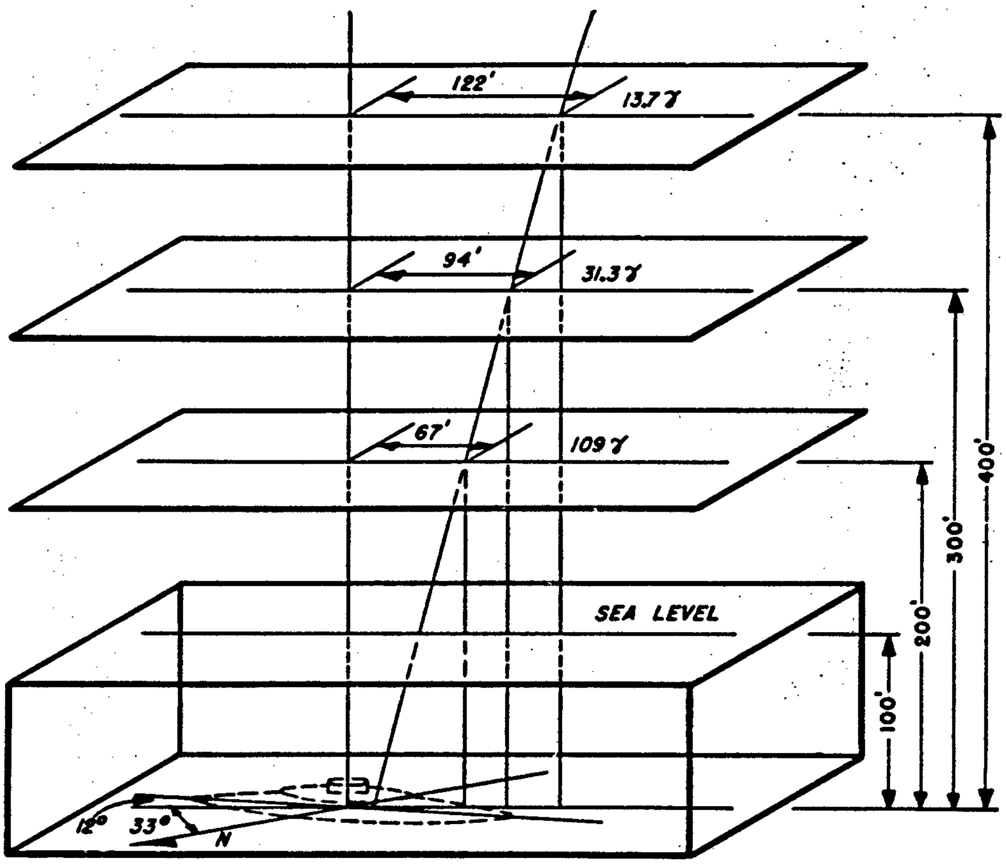


FIGURE 9. Variation of intensity and position of "peak" of submarine field with elevation.

may be secured. The detecting element is arranged to be moved over the chart and means are provided for marking its position thereon at any time.

The submarine model comprises three mutually perpendicular coils mounted on a turntable capable of 360° rotation. This turntable is mounted on a screw-type elevator, by means of which its separation from the top of the drafting table may be adjusted. The drafting arranged to rotate about a horizontal axis, the orientation of which is fixed in respect to the table top, this axis being the perpendicular bisector of the longitudinal axis of the coil. One direction on the table top, along which lies the projection of the longitudinal axis of the pickup coil, is chosen as (magnetic) north and all headings of the submarine are measured with this as a reference. The horizontal axis about which the coil may be rotated then extends in the

east-west direction so that the angular position of the detector coil corresponds to the dip angle. The voltage induced in the coil as it passes over the field of the submarine is measured by means

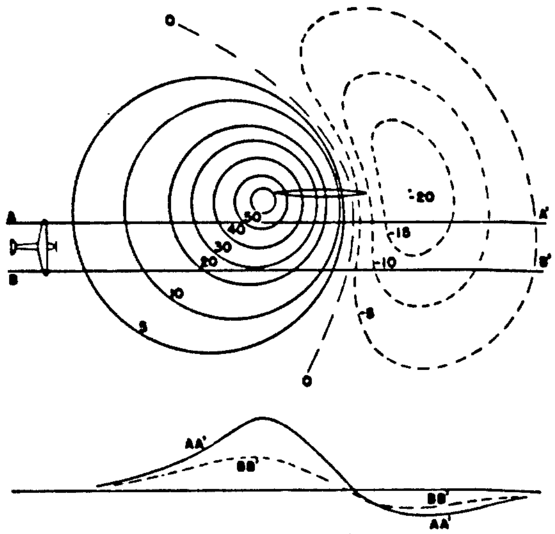


FIGURE 10. Field variations and response signals for a case of dual MAD installation at the wing tips of an airplane.

of a vacuum tube voltmeter. This meter is calibrated to read directly in gammas in the following manner.

The detector coil is placed directly over the center of the submarine and is oriented vertically. Excitation is then supplied to the coil generating the vertical moment of the submarine, and the separation between the center of the submarine and the coil is measured. The amount of the excitation is varied, using the gain control of the appropriate amplifier until the output vacuum tube voltmeter reads a convenient value, say, 10. The scale on which reading is obtained is noted and the reading is designated as that corresponding to a 10-gamma signal. The excitation supplied to the submarine coils is read in amperes. Using the separation between detector and submarine previously noted and the arbitrarily chosen value of the field at the detector, the moment produced by the coil is calculated using dipole equations. The calibration factor relating moment in cgs units and excitation current in amperes may then be calculated for the coil generating the vertical moment.

The calibration factors for the other two submarine coils may then be determined with reference to that just determined. For this purpose the detector is reoriented in such manner that it is parallel to the longitudinal axis of the submarine. Excitation is then supplied only to the submarine coil generating the longitudinal moment, the separation between the detector

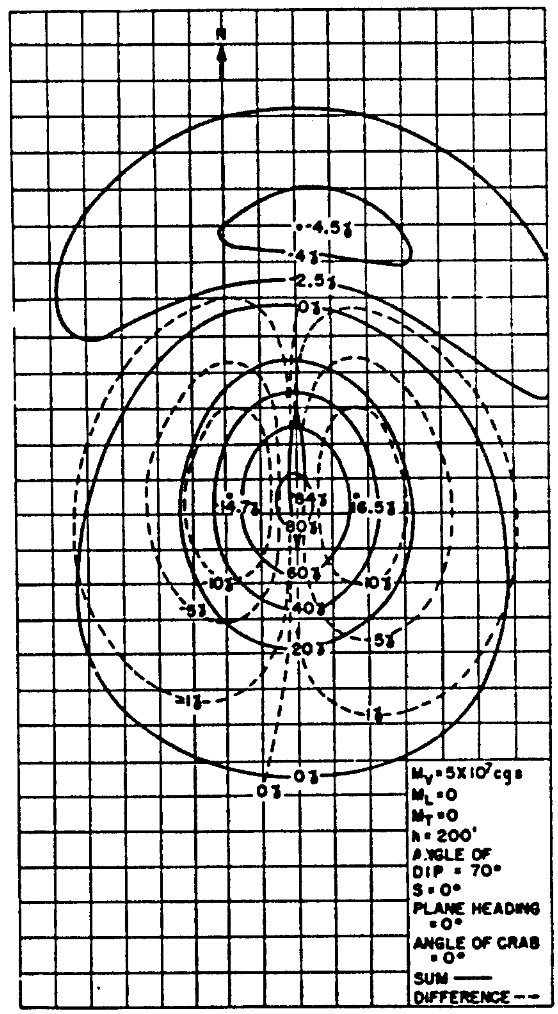


FIGURE 11. Sum and difference contour chart for 50-foot separation of detectors, with plane heading N at all points.

and the coil being held at the value used in the first calibration. The excitation is then varied until the detector voltmeter reads one-half the value previously used. (When the axes of the detector coil and the coil in which the field is

generated are parallel, the output of the coil is one-half the output which results when the axis of the detector coil forms an extension of that of the generating coil.) The excitation current

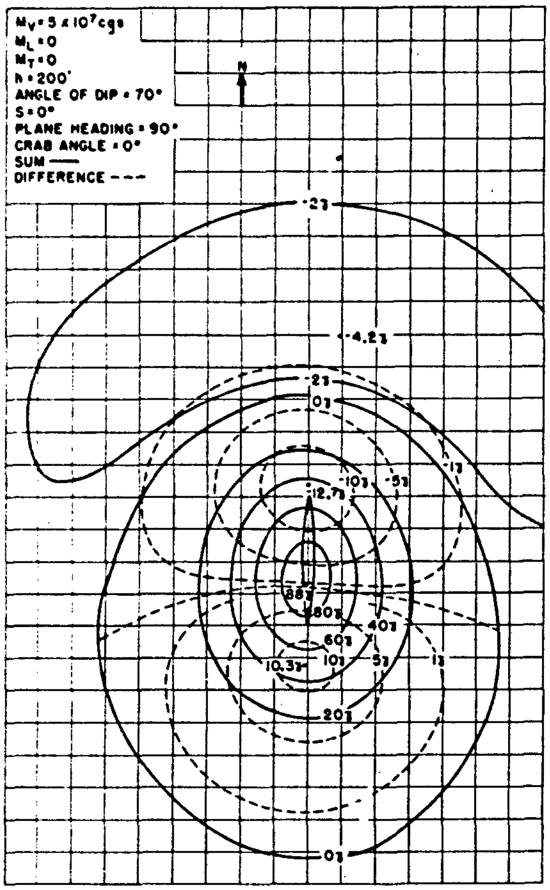


FIGURE 12. Sum and difference contour chart for 50-foot separation of detectors, with plane heading E at all points.

in amperes is then read and the calibration factor for the longitudinal moment calculated from that for the vertical moment, using simple proportions. The calibration factor for the transverse moment is obtained by a similar procedure, the detector coil being oriented with its axis parallel to the transverse axis of the submarine.

In addition to determining the calibration factors for the coils generating the three moments, it is also necessary to determine the phasing of the excitation in each for the purpose of simulating the polarity or direction of the moment generated thereby. For this purpose the phase of the excitation in each coil must be measured relative to that of a reference signal and some phase relation designated as representing one polarity of moment. For this measurement the detecting element is first placed in its vertical orientation directly over the center of the submarine model. The lower end of the element is marked and thereafter designated as the *N* pole. Excitation is then supplied to the coil generating the vertical moment for the

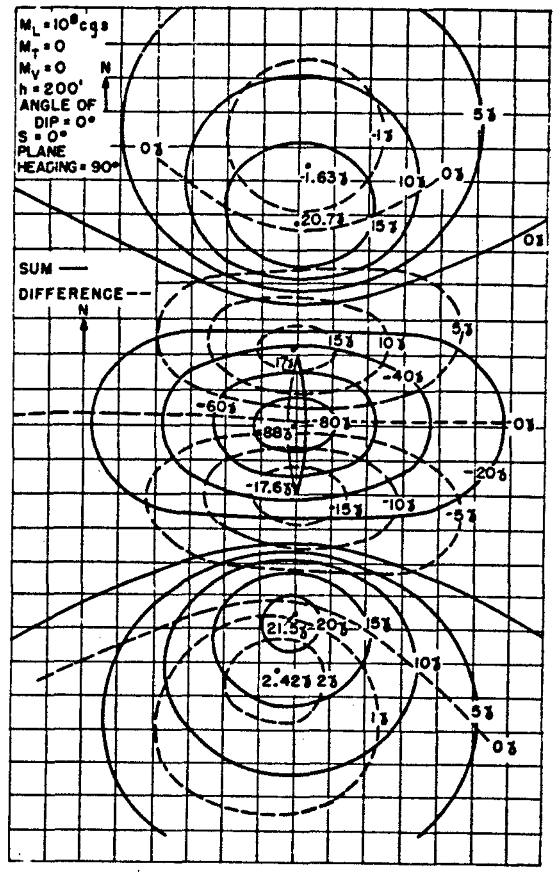


FIGURE 13. Sum and difference contour chart for submarine at low dip angle. Detector separation is 50 feet.

submarine. The excitation to the submarine coil is also impressed upon the horizontal sweep circuit of a cathode-ray oscilloscope while the signal from the detector is impressed upon the vertical axis input of the same oscilloscope.

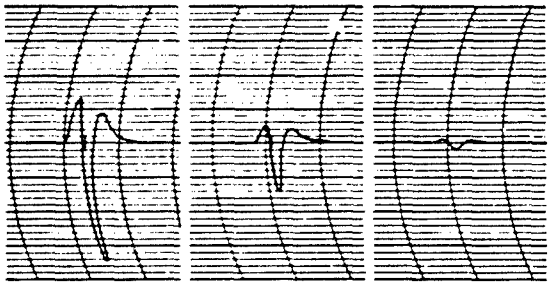


FIGURE 14. Model signals. Target is vertical dipole; dip angle 70°; blimp heading N at 20 knots and 200 feet elevation. Lateral displacement of path from target center: (A) 0 feet; (B) 100 feet; (C) 200 feet.

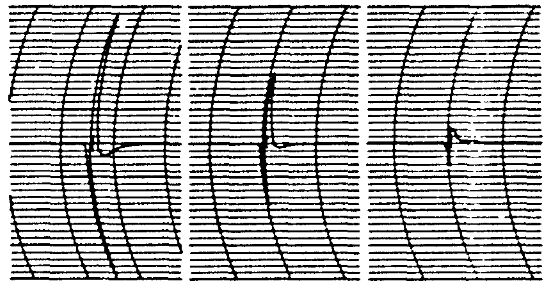


FIGURE 15. Model signals. Target is vertical dipole; dip angle 70°; blimp heading N at 80 knots and 200 feet elevation. Lateral displacement of path from target center: (A) 0 feet; (B) 100 feet; (C) 200 feet.

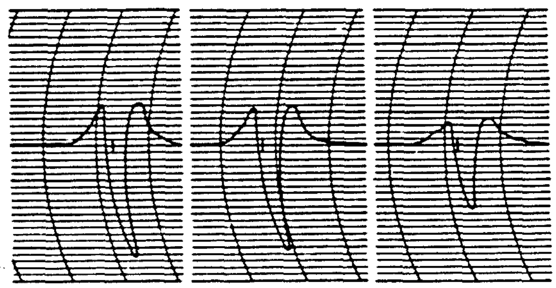


FIGURE 16. Model signals. Target is vertical dipole; dip angle 70°; blimp heading N at 20 knots and 400 feet elevation. Lateral displacement of path from target center: (A) 0 feet; (B) 100 feet; (C) 200 feet.

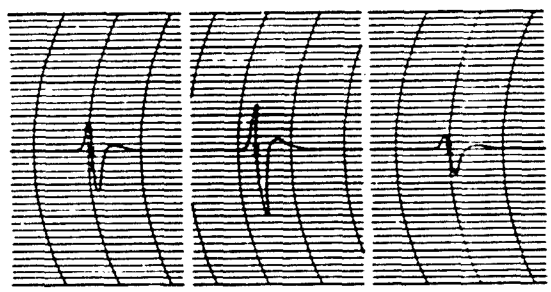


FIGURE 17. Horizontal dipole directed N, dip angle 70°, blimp heading E at 40 knots, 200 feet elevation. (A) 0 feet displacement; (B) 100 feet displacement; (C) 200 feet displacement.

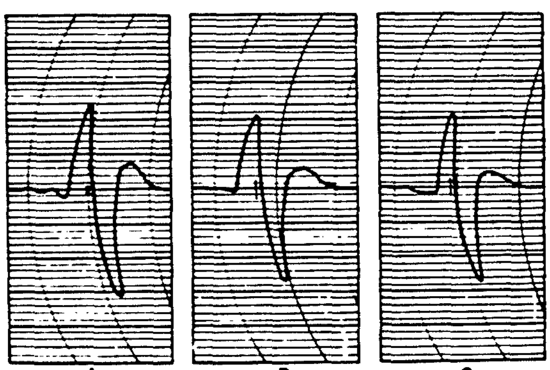


FIGURE 18. Horizontal dipole directed N, dip angle 30°, blimp heading N at 20 knots, elevation 400 feet. (A) 0 feet displacement; (B) 100 feet displacement; (C) 200 feet displacement.

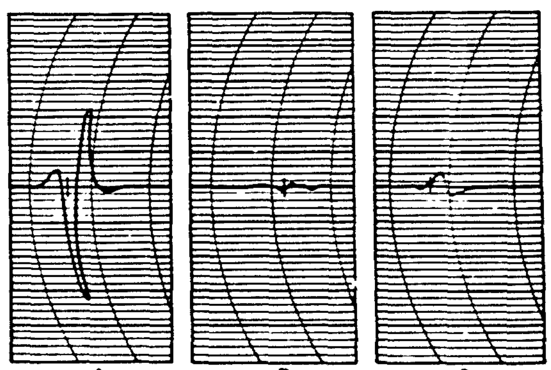


FIGURE 19. Horizontal dipole directed E, dip angle 30°, blimp heading E at 20 knots, 200 feet elevation. (A) 0 feet displacement; (B) 100 feet displacement; (C) 200 feet displacement.

The two signals will ordinarily be either in phase or 180° out of phase, depending upon the position of the reversing switch associated with the vertical moment coil. Since the positive vertical moment of a submarine is always taken as downward, the signal picked up by the detector may be designated as positive. The sign of the slope of the trace on the oscilloscope is noted and the position of the reversing switch designated as positive.

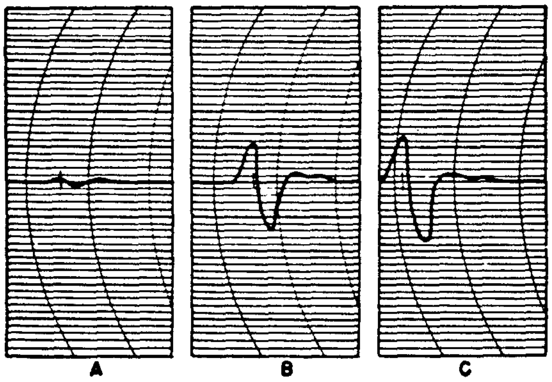


FIGURE 20. Horizontal dipole directed E, dip angle 70°, blimp heading E at 40 knots, 200 feet elevation. (A) 0 feet displacement; (B) 100 feet displacement; (C) 200 feet displacement.

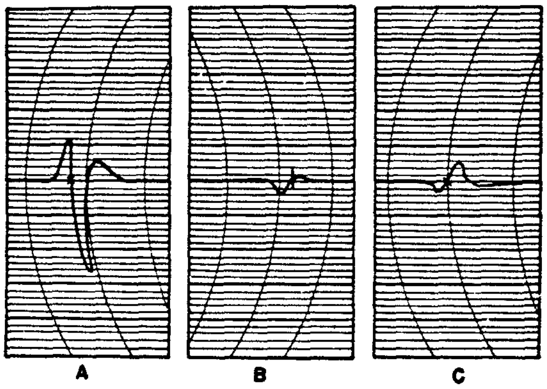


FIGURE 21. Vertical dipole directed N, dip angle 30°, blimp heading N at 20 knots, elevation 400 feet. (A) 0 feet displacement; (B) 100 feet displacement; (C) 200 feet displacement.

The submarine model is then placed on a north heading, one end of the model always being designated as the bow, and the detector

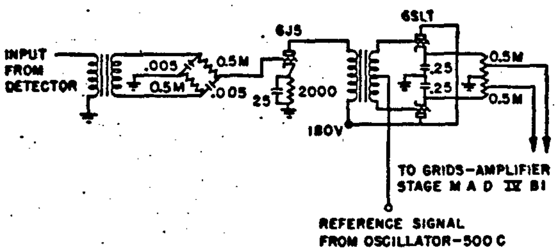


FIGURE 22. Demodulator for a-c dynamic signal system.

is oriented with its axis parallel to the longitudinal axis of the submarine and with its N pole to the north. The coil generating the longitudinal moment of the submarine is then excited and the relative phase of this excitation and the signal picked up by the detector compared through the use of the cathode-ray oscilloscope, as described above. Since the longitudinal moment of the submarine is taken as positive when it extends from stern to bow thereof, the geometry of the system indicates that a negative signal will be received by the detector. Therefore, if the trace on the oscilloscope has a slope opposite in sign to that observed with the vertical moment, the position of the reversing switch is marked as positive; otherwise, it is marked negative.

The same procedure is repeated for the coil generating the transverse moment, the positive transverse moment of the submarine being taken as extending from east to west while the submarine is on a north heading. In this case the detector is oriented with its N pole to the west so that a negative signal is again to be expected. If the slope of the trace on the oscilloscope is opposite in sign to that observed using the coil generating the vertical moment, the position of the reversing switch is marked positive as in the case of the coil generating the horizontal moment.

A further determination of polarity is made, using the detector in its vertical orientation and exciting all three coils, the phases of the three excitations having previously been adjusted to be the same. The relative phases of the excitation to the coils and that of the signal picked up by the detector are compared, using the cathode-ray oscilloscope. The total resultant moment of the submarine is taken always to

point downward when positive so that, if the trace has a slope of the same sign as that observed in the case when only the vertical moment coil is excited, the signal may be said to be positive. This fact is noted for future use in determining the sign of signals. It should be noted that if an overflashed submarine is to be reproduced, the vertical moment must be given a negative polarity.

of H in the vertical section through the submarine, these charts show *lines of constant magnitude of the component of H parallel to the earth's field* throughout a horizontal plane above the submarine. The charts can be most easily described by specifying the location of the "peaks" or point of maximum anomaly field strength.[a] Table 2 is a compilation of the most usual cases for north magnetic latitudes.

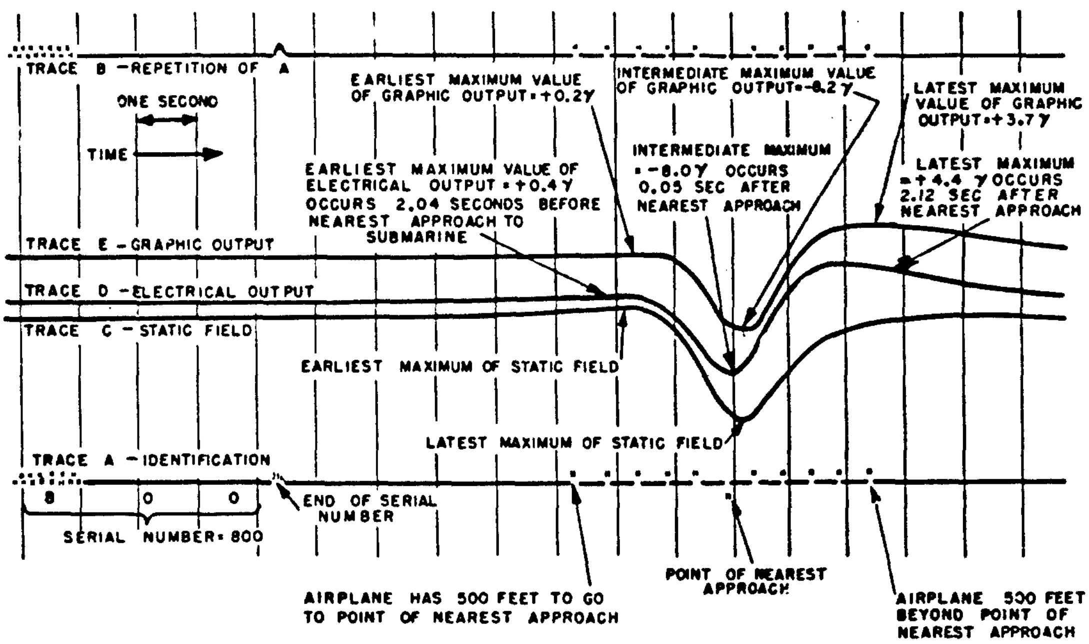


FIGURE 23. Specimen record obtained by the a-c dynamic signal technique.

4.1.2 Contour Charts

Sixty contour charts were made up[5] covering various combinations of the variables over the following ranges.

Elevation:	200 – 400 feet
Transverse moment:	0 – 0.18 × 10⁸ cgs units
Vertical moment:	0 – 5 × 10⁸ cgs units
Longitudinal moment:	0 – 5 × 10⁸ cgs units
Submarine heading:	0 – 315°
Dip angle:	0 – 90°

Typical cases are shown in Figures 3 to 8. Whereas Figure 1A shows the lines of *direction*

The patterns for south magnetic latitudes are symmetrical to those here listed. Patterns for different elevations are similar, those at greater heights being merely weaker and more spread out, as indicated by Figure 9.

SUM AND DIFFERENCE CONTOUR CHARTS

As will be discussed in Chapter 5, the effort was made in the AN/ASQ-2 dual system to get more precise information about the submarine's location by using two laterally displaced MAD systems, one at each wing tip of an airplane, for example. Figure 10 shows the resulting signals for a simple case. The recorder might be made

[a] These are not identical with the peaks of the MAD signal, which may come at different points depending on the plane's path across the contours.

to indicate the difference or the sum, or some other combination of the two output voltages which might give a better measure of the position of the submarine. In order to explore the possibilities of such a system a number of contour charts were made on the plotting table here described using two appropriately spaced detector coils, with their outputs added or subtracted electrically. Figure 11 illustrates a typical simple case. The difference voltage has strongly dependent on the plane's heading, as is brought out by a comparison of Figure 11 and Figure 12. One of the somewhat less simple cases is given in Figure 13.

4.2 DYNAMIC SIGNAL STUDIES

Much of the usefulness of the contour charts comes from the fact that the variations which

TABLE 2. Summary of types of submarine field patterns to be expected in north magnetic latitudes.

Dip angle in degrees	Submarine headings in degrees	Type of longitudinal magnetization	Peaks: Number observed	Peaks: Position (approx.)
80 to 45	0 or 180	Perm. and induced	Two (1+ and 1−)	On a N-S line over submarine.
		Induced only	Two (1+ and 1−)	On a N-S line over submarine.
	45, 135, 225, or 315	Perm. and induced	Two (1+ and 1−)	On a line parallel to submarine.
		Induced only	Two (1+ and 1−)	On a line approx. parallel to submarine.
	90 or 270	Perm. and induced	Two (1+ and 1−)	On an E-W line a little south of submarine.
		Induced only	Two (1+ and 1−)	On a N-S line over submarine.
45 to 0	310 to 50 or 130 to 230	Perm. and induced	Three (2+ and 1−) or (1+ and 2−)	Like peaks on a line over some part of submarine.
		Induced only	Three (2+ and 1−)	On a line approx. parallel to submarine.
	50 to 130 or 230 to 310 (approx.)	Perm. and induced	Four (2+ and 2−)	Lines through like peaks cross near submarine center.
		Induced only	Three (2+ and 1−)	On a N-S line over submarine center.

opposite sense on the two sides of the sum peak, of course, and so it might well be used to operate a right-left indicator. (It should be noted, however, that the difference will indicate the direction of the nearest strong peak, which is not *always* necessarily the direction toward the submarine.) Of course the difference voltage is an MAD detector would encounter on any chosen path through the submarine's field could be determined by drawing the path on the chart and plotting field amplitude as a function of detector position. It must be noted, however, that the curves thus obtained will not exactly correspond to the output signal from the MAD

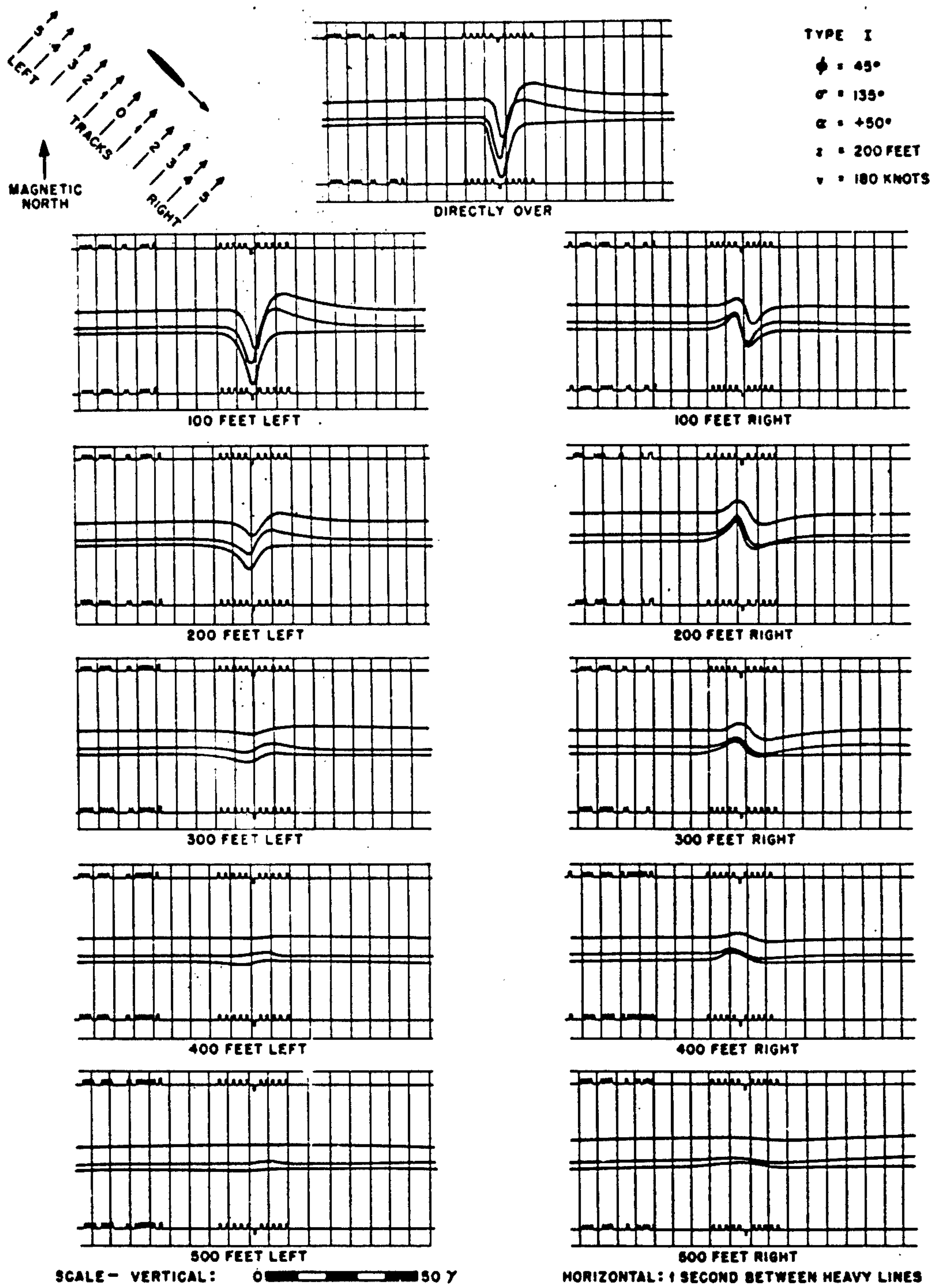


FIGURE 24. Dynamic signals obtained by the a-c coil method.

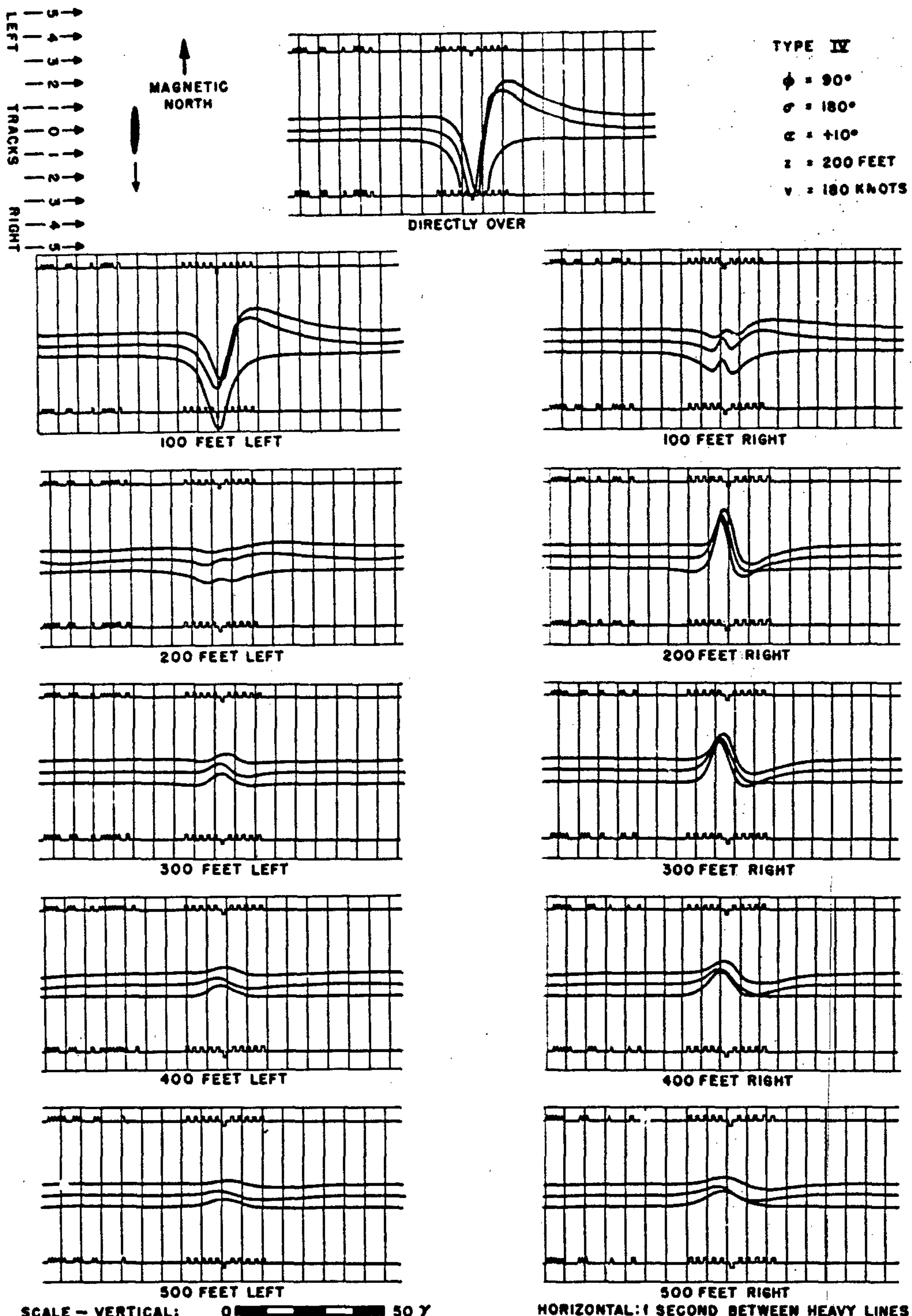


FIGURE 25. Dynamic signals obtained by the a-c coil method.

equipment, because all detection systems include reactive impedance with a definite time constant. The resultant filter action is such that variations in electric output differ appreciably from variations in the magnetic field, as was shown in Figure 23 of Chapter 3. A more accurate picture of the kind of signal to be expected on the recorder from any given situation

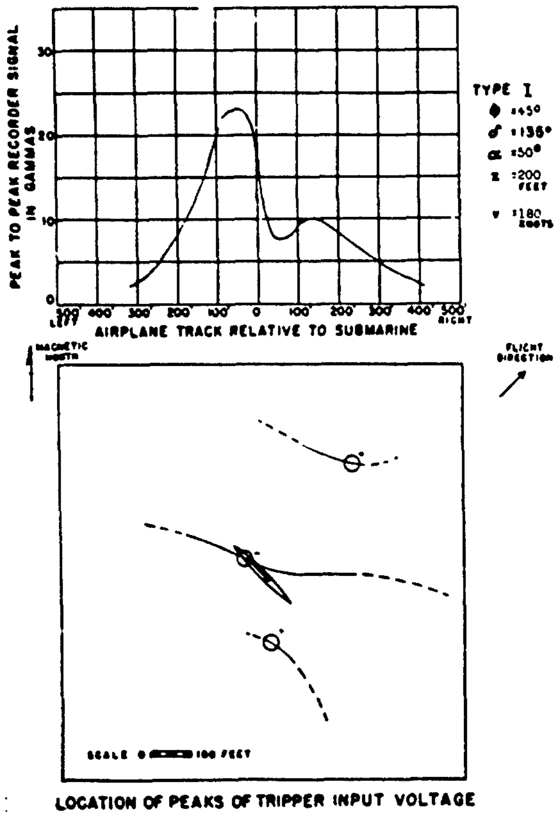


FIGURE 26. Peak-to-peak amplitude graph and peak position map obtained from data of Figure 24.

may be obtained by moving a submarine model in the proper fashion past a detector which feeds an actual AN/ASQ-1 amplifier.[b]

The Permanent Magnet System

Two systems were used for simulating dynamic signals. In the first a trolley moved a permanent magnet, the field of which simulated that of a submarine, along a given path past a fixed detector. The detector was a standard MAD head with the orientors disengaged. The fluctuations in the ambient field in the laboratory do not cause quite as much trouble here as in the static experiments because the AN/ASQ-1 filter networks discriminate against frequencies other than those contained in the usual submarine signal. The head was oriented at the dip angle to be simulated, and the earth's field was compensated by using the bias circuit of the MAD detector. The orientation of the permanent magnet was then adjusted to reproduce the total field of a submarine at the geographical location under investigation. Provision was made for varying both the vertical distance and the lateral displacement between the submarine model's plane of travel and the detector, while the speed of the model along its path represented the speed of the aircraft. Several hundred cases were investigated.[7] The most usual signals were of the type shown in Figures 14 and 15, which simulate the records obtainable on a blimp traveling at 20 and 80 knots respectively. On each of these records a short vertical line or a cross marks the time of closest approach to the target. The time scale is 30 seconds per chart division. The sensitivity is not the same for the different figures, but it is the same for the three records of each figure.

Although Figures 14 and 15 show the most usual case, there occur conditions where the peaks for 0, 100, and 200 feet lateral displacement of the path from the target have other relative magnitudes (Figures 16 to 20), or where corresponding peaks are not of the same sign at each displacement (Figure 21). Such complications are to be expected, of course, in view of the varied types of static contour maps which may occur.

The A-C Coil System

The use of the model equipment with which the contour charts were made for the study of dynamic signals is entirely possible, if means are provided for moving the detecting element across the surface of the charting table at a scaled speed and for introducing the signal

[b] Of course any of the possible signal patterns may be derived mathematically if suitable expressions are known, or can be assumed, for the behavior of the amplifying circuits. For work in this line see reference 6.

picked up thereby into a replica of standard MAD equipment. In view of the fact that field patterns for a submarine of given magnetization are similar regardless of the altitude at which they are measured, it will be understood that the speed at which the detecting element is moved across the charting table must be scaled using the same scaling factor as is used for this purpose. Once such runs have been made, the rheostat controlling the speed of the motor may be calibrated directly in scale miles per hour.

Since the submarine model is provided with alternating current excitation, the output of the detector, as it is moved thereover, will be essentially a modulated 500-cycle wave, the carrier

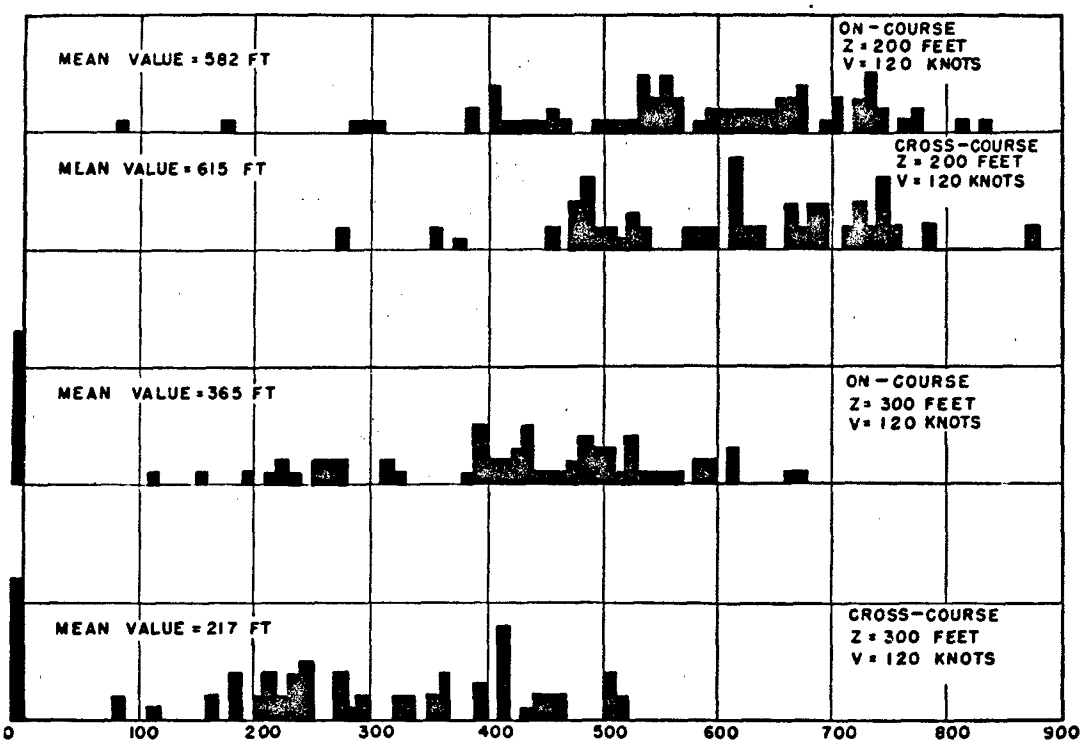


FIGURE 27. Frequency distribution of search widths in feet for peak-to-peak recorder signals greater than 5 gammas.

in scaling the separation between the detector and the submarine.

In the model the detector is arranged to be moved across the plotting table on any heading by a towing device. Mechanism for carrying the detector over the submarine model comprises a pair of parallel tracks supported by a frame which may be placed on the table top and a wheeled carriage which bears the single detector airplane model and may be drawn along these tracks by means of an electric motor. The relationship between motor voltage and scale speed may be determined through the use of a stop watch, several timing runs being required frequency being the frequency of excitation supplied to the submarine coils. Since the carrier signal is sinusoidal, the demodulator stage of standard MAD equipment cannot be used in the model setup. It can be shown, however, that if a suitable demodulator circuit is substituted for the demodulator stage of the MAD equipment and the output of this circuit is fed through the remainder of the MAD detector equipment, dynamic signals will be recorded on the Esterline-Angus meter. These signals will in every way correspond with those actually obtained in practice, using the standard detector.

The model equipment includes the simple demodulator illustrated in Figure 22. The signal is introduced through an input transformer to the grid of an amplifier tube. The output of this tube is transformer-coupled to a push-pull demodulator stage, and as shown in the diagram a reference signal from the oscillator providing excitation to the submarine model is introduced

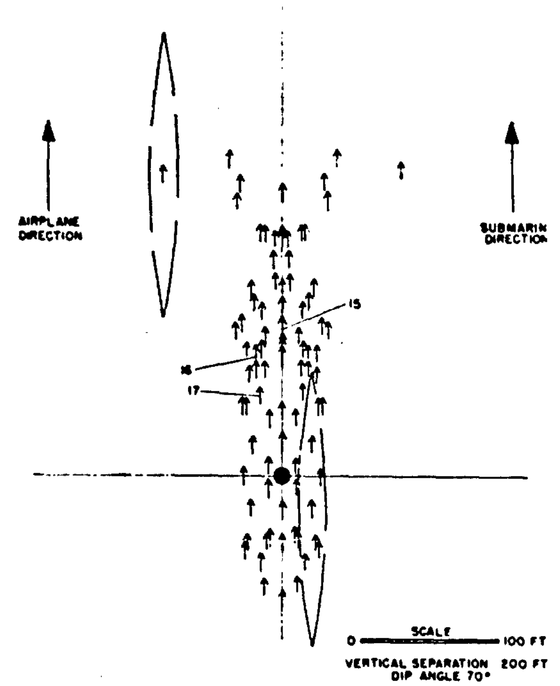


FIGURE 28. Possible positions of submarine center when MAD registers a peak at position of small solid circle, with plane and submarine courses known to be parallel.

at the center tap in the secondary of the coupling transformer. This arrangement is necessary in order to get true reproduction of the signal as it goes first positive and then negative or vice versa, the signal from the amplifier stage being added to and subtracted from the reference signal in the two sides of the demodulator circuit. In view of this fact it is necessary that the phase of the input signal correspond to that of the reference signal, and for this purpose the resistance-capacitance network indicated in the diagram is interposed between the input transformer and the amplifier tube. The output signal is taken from the two potentiometers shown in the diagram, and, since the common point of these two resistors is grounded, the signal may be used push-pull and may have both positive and negative polarity. This signal is introduced to the grids of the amplifier stage of the standard MAD detector unit and the output thereof is recorded on an Esterline-Angus meter in the same manner as in service.

Provision was also made to record the static field at each point and the electric output of the AN/ASQ-1 circuit as well as the recorder output. Figure 23 is a specimen trace showing the type of information to be found on such records. Several thousand such test runs[8] were made with different combinations of the variables of position and with four different combinations of submarine moments. Figures 24 and 25 are cases occurring at 50° and 10° dip angle, respectively.

The chart for each test was analyzed[9] and the peak-to-peak amplitude of the graphic output was measured for each run. This information was plotted against lateral separation to form a graph as shown in the upper part of Figure 26.

In addition, peak position maps[10] were made for the electric output. For all test runs the distances of the output maxima along the line of flight, from a vertical perpendicular through the center of the submarine were plotted and the points connected. A solid line, as shown in the lower drawing of Figure 26, indicates peak amplitudes greater than 5 gammas; and broken lines, less than 5 gammas but greater than 2. Figure 27 is a statistical analysis of some of the results.

The following conclusions were drawn from this series of studies.

1. Peaks over 2 gammas high will occur in a range from about 250 feet before to 125 feet after the center of the submarine for on-course runs and in a range from 150 feet before to 125 feet after the center for cross-course runs. These figures are based on dead-over airplane flights between 200 and 300 feet above all four submarine types studied.

2. The search width[e] for the submarines rep-

[e] Search width is defined as that distance at right angles to the direction of flight at a given altitude within which an Esterline-Angus (E-trace, Figure 23) peak-to-peak amplitude of at least 5 gammas will be recorded.

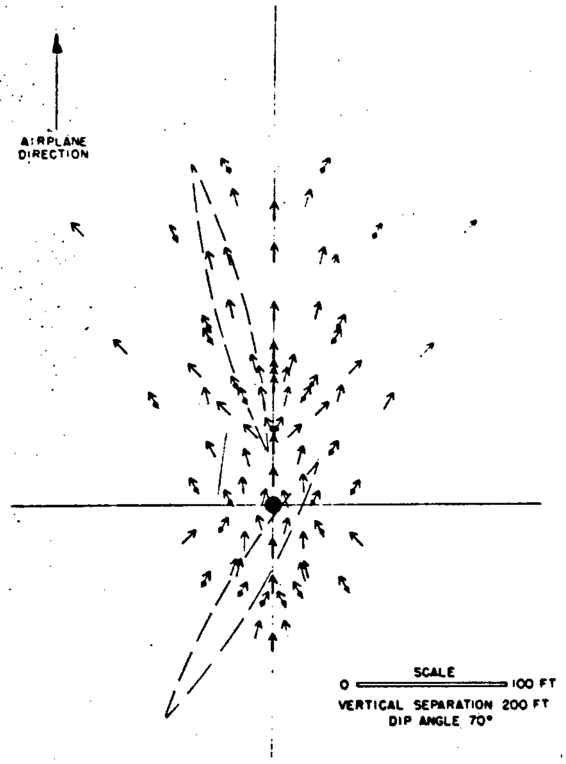


FIGURE 29. Same as Figure 28, except that submarine heading may be random.

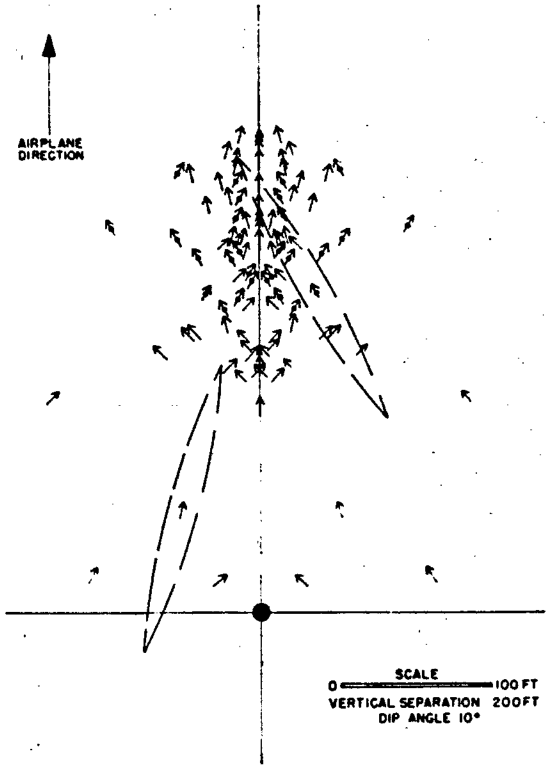


FIGURE 30. Same as Figure 29—at dip angle 10°.

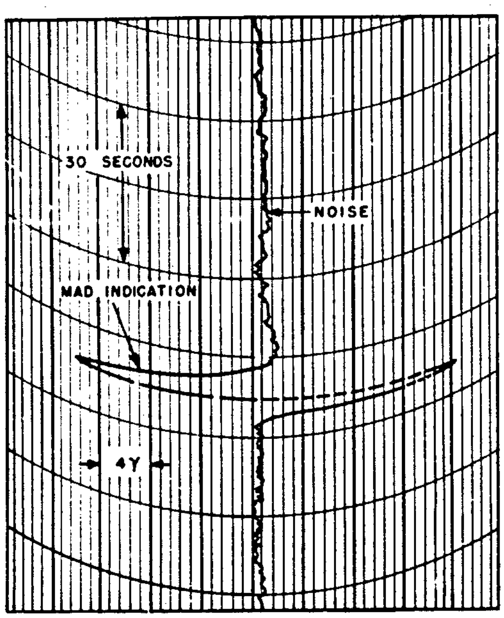


FIGURE 31. Section of a typical MAD signal on a wrecked steamer.

sented in this study is about 600 feet at a 200-foot vertical separation and about 320 feet at a 300-foot separation.

3. The signal intensity diminishes more rapidly than the inverse ratio of the vertical separations cubed. Its magnitude decreases roughly as the 3.7 power of the inverse ratio of the two separations for on-course runs and at a slightly higher rate for cross-course runs.

4. The mean value of the time index[d] of the C-trace at 120 knots for on-course runs at a 300-foot separation is 1.75 ± 0.15 seconds. The frequency of the C-trace will vary directly with the speed and inversely with the separation over a limited range.

The time index of the E-trace for speeds between 120 and 180 knots at separations of 200 to 300 feet lies, for the most part, between 1.0 and 2.4 seconds. (These values are of impor-

[d] The time index of an indication is the time taken to record its peak of minimum duration. The duration of a peak is shown on the record as the distance on paper between the start and end of the peak.

tance in fixing the frequency characteristics of the inputs to the d-c amplifiers in the detector and bomb-firing circuits.)

Another type of generalization[11] which can be drawn from these records is illustrated by Figure 28. This shows the positions of the centers of a wide magnetic assortment of submarines with respect to the first peak in the field encountered on a run made *on-course* with the target, as might occur in combat when the submarine heading has been observed just before submergence or has been plotted from a

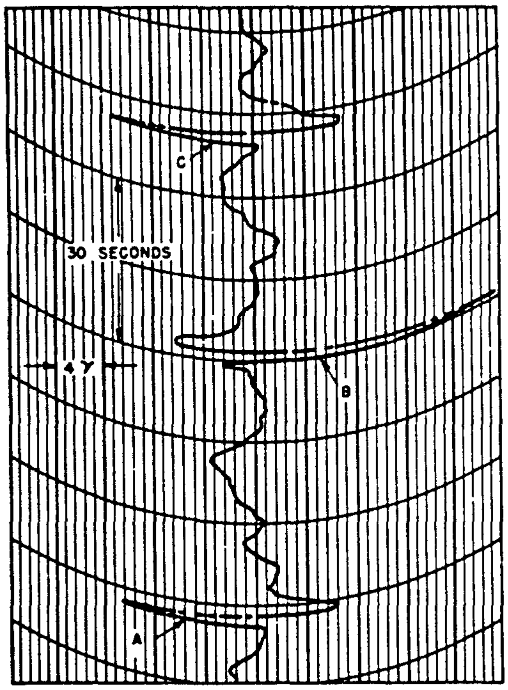


FIGURE 32. Submarine signals. Altitude 100 feet, airplane ground speed 140 knots, submarine 50 to 100 feet below surface. The heading of the airplane was different for each pass.

series of earlier signals. The large solid circle represents the first peak encountered. The arrows represent the *centers* of possible targets. The complete target outline is shown for only two cases to avoid the confusion which would result from overlapping in the diagram. Figure 29 is a similar compilation for a situation where the submarine heading is not known, so all possible headings are included. A case in the low magnetic latitudes is given in Figure 30. It will be observed that although the airplane is usually quite close to the target when it encounters the first peak, there are times (Figure 30) when it would be better to release a bomb a few seconds *after* passing the first peak.

4.3 TYPICAL FIELD RECORDS

Based upon operating experience and upon laboratory studies with models a number of rules were derived for distinguishing between valid signals and unwanted fluctuations due to geological anomalies, violent fluctuations in power supply, etc. These rules give an indication of the behavior of the system in the field.

Rule 1. The first peak of a true MAD signal will not break sharply from the center line but will begin gradually.

Rule 2. The time index of a submarine signal will not be less than ¾ second nor more than 5 seconds for distances from the PBY plane to the submarine between 100 and 500 feet.

Rule 3. An MAD signal will never have more than five peaks and rarely more than four.

Rule 4. If the size of one peak of an MAD signal is off scale, then the signal will have at least one additional peak showing above the noise level and will frequently have at least two additional peaks.

Rule 5. Under conditions of normal noise level the trace of an MAD signal should be free from irregularities, with the possible exception of the first or last peak, if they are small.

Some field records[12, 13] illustrating these rules are shown in Figures 31 to 36.

4.4 MAD TACTICS

Using the signal studies described in this chapter, as well as reports from the field, a considerable amount of research on MAD tactics[14-16] was carried out. Probabilities of success were computed for various trapping maneuvers, tracking maneuvers, and bomb runs. Figure 37 shows one of the more favorable and widely used systems: the clover-leaf pattern. Circular and spiral search patterns are also useful.

Since the range of MAD is measured in hundreds of feet rather than in miles, its principal tactical use is in detecting, tracking, and locating a submarine which has been sighted or

detected by radar at a distance and has then submerged as the airplane approached it. The general procedure in such a search and attack operation is as follows.

1. A visual or radar contact is made with the target at a distance.

2. The plane flies to the spot where the target was last observed, the target meanwhile having submerged.

3. The probable point of submergence is marked and the plane executes search or trapping tactics until an MAD signal is obtained indicating the presence of the submarine within the detection range. This point is marked with float lights or slicks or some other marking device.

4. The plane then executes tracking tactics, marking each successive MAD signal. The line of markers then indicates the submarine's track.

5. After establishing this track, the plane makes a bombing attack with one of several types of ordnance. In some cases, the ordnance is released by automatic control, using the MAD signal.

The nature of the attack, of course, depends upon the type of ordnance used. There are three distinct types which are known as follows:

1. Depth charges.
2. Mousetrap ammunition: contact bombs.
3. Retro-fired, rocket-propelled mousetrap ammunition: contact bombs.

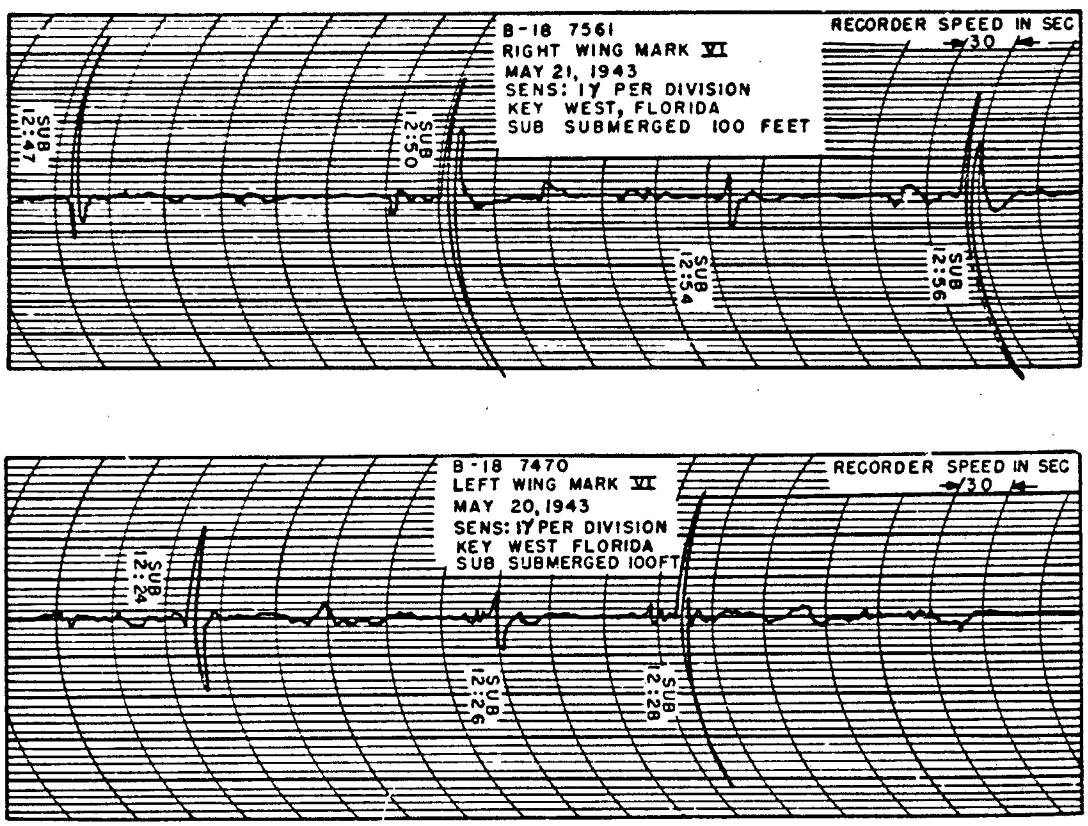


FIGURE 33. Record of a number of passes over a submarine submerged 100 feet.

Depth charges and ordinary mousetrap bombs fall forward because of their initial forward velocity. Hence, they are released on a bombing run toward the target at a point sufficiently in advance of the estimated target position to enable them to fall on the target.

In order to estimate the target position, the submarine is tracked by its magnetic anomaly;

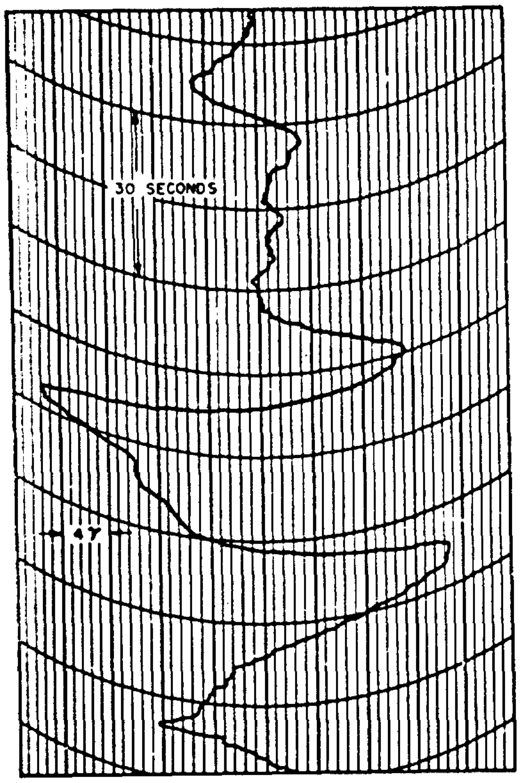


FIGURE 34. Spurious indication of geological origin.

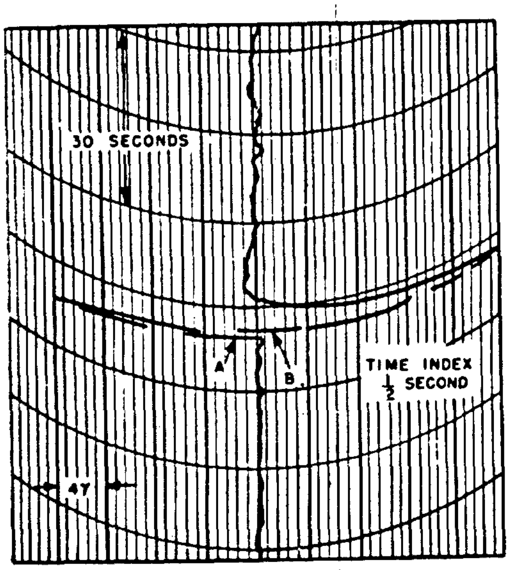


FIGURE 35. Spurious indication caused by fluctuation in airplane's power supply.

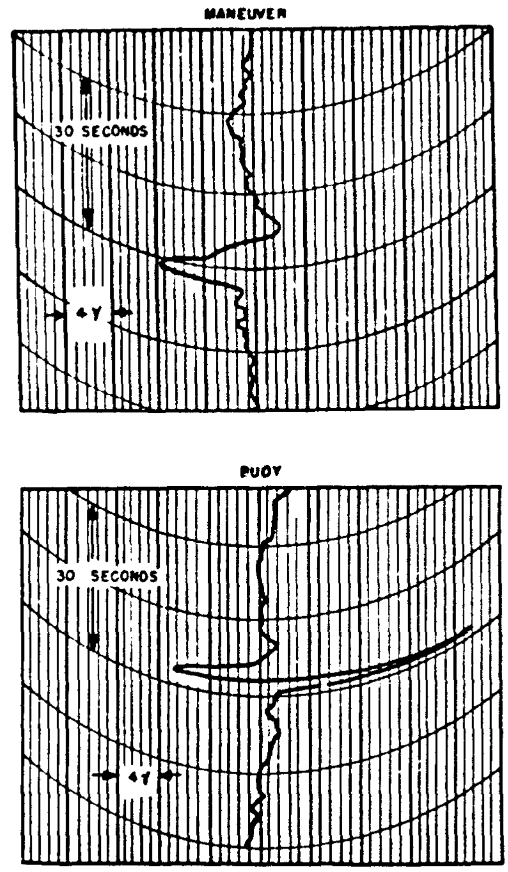


FIGURE 36. Comparison of signals resulting from maneuver of airplane and from a large buoy.

every time the plane flies through this anomaly a marker is dropped. When a series of these markers has been put down, the pilot or bombardier is in a position to see the submarine's track and to project it forward of the last marker. Also, from the spacing of the last two markers and a knowledge of the interval between the instants at which they are dropped, he may predict the position of the target along the extrapolated track. The bombing run is then set up to cross this point and the bombs are released in a line or pattern at points along the airplane's track which will center the pattern on the estimated target position. Thus, when forward falling bombs are employed, the MAD may be used to establish the submarine's track, but because on the bombing run the bombs must be released before the plane arrives over the target, it is not used directly to establish the

bombing point other than by estimation, as mentioned above.

Retro-bombs are used for vertical bombing. Hence there is no need to release them before the plane arrives over the target. This makes it possible to use the magnetic signal obtained

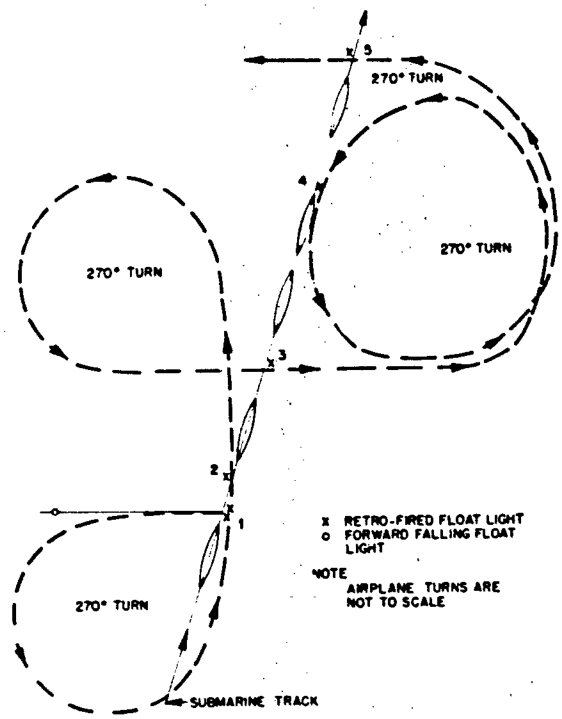


FIGURE 37. The clover-leaf tracking pattern.

when the plane flies through the submarine's field to establish the bombing point. In this way automatic bombing controlled by the magnetic signal becomes possible. Thus the use of retro-bombs eliminates the need of predicting the target position by visual judgment and calculation and substitutes a direct positive indication which tells when the bombing point has been arrived at and which may be used to control automatic bomb release mechanisms.

In the tracking operation markers are required. There are available for this purpose the following types.

1. Slicks (aluminum, bronze, fluorescein, rhodomine).
2. Float lights (Mark IV, 3 to 5 minutes burning time) (Mark V, 10 to 15 minutes burning time).
3. Float lights, retro-fired (Mark V).
4. Retro-fired slicks which are under development.

Slicks are used only in daylight operations. Float lights may be used at any time. Retro-fired float lights have a vertical trajectory and, therefore, mark the spot where the MAD signal maximum was obtained more accurately than do the markers which are simply dropped from the airplane. For example, when a float light is dropped from a plane moving at 200 feet per second ground speed at an altitude of 100 feet, the marker lands on the water at a point nearly 500 feet forward of the point directly under the place where it was released.

Automatic equipment for releasing both

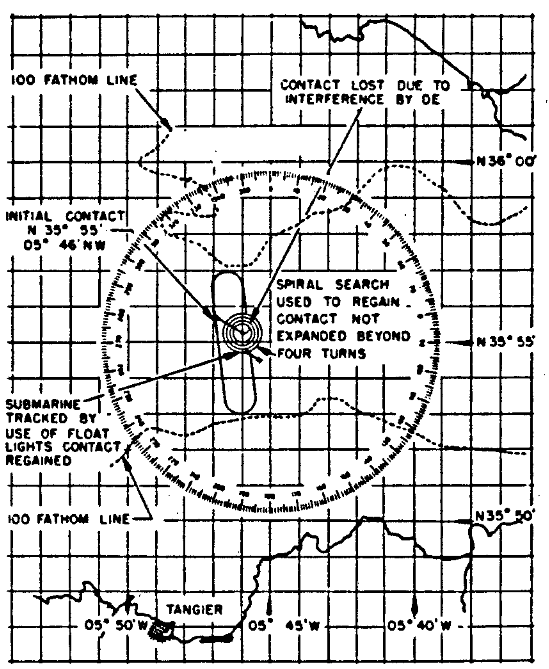


FIGURE 38. Chart of MAD action against a submarine in the Straits of Gibraltar.

markers and bombs at the instant the maximum of the MAD signal is obtained, or at a predetermined time thereafter, will be discussed in the next chapter. This automatic equipment may be used for marker release (especially retro-fired float lights) in the search and tracking operation. When retro-bombs are used, the automatic equipment may be employed to control their release.

The following is an excerpt from a report on a successful attack, illustrated by Figure 38, in the Straits of Gibraltar.[17]

U-Boat Contact and Attack by VP-63,
February 24, 1944

(a) Time—15:59.
(b) Own Course—171° True.
(c) Own Speed—100 knots.
(d) Altitude—100'.
(e) Sub Course—120 (m).
(f) Sub Speed—2-2½ knots (estimated).
(g) Contact made by MAD on routine mission.
(h) MAD operator fired first flare.
(i) Second contact established by use of VP-63 spiral tactics.
(j) Number of signals obtained by plane No. 14-11.
Number of signals obtained by plane No. 15-10.
(k) Maximum signal obtained—40 gamma.
(l) Minimum signal obtained—4 gamma.
(m) Average signal obtained—10.5 gamma.
(n) Average duration of signals—7.2 seconds.

The original contact was made by MAD at 35° 56′ N—05° 47′ W by PBY No. 15. Two smoke lights were fired on original contact. After three lights had been laid in clover-leaf pattern, PBY No. 14 joined in tracking 180° relative to plane No. 15.

Contact persisted on track approximately 120° N at a speed of approximately 2-2½ knots. No. 15 was within magnetic field on each clover-leaf pass. After 5 lights had been laid by plane No. 15, a British DD made a run down the line of float lights fouling area of MAD contact. The DD planned to attack but lost contact. After the DD passed through, magnetic contact could not be reestablished—time approximately 16:22. A search was started using the clover-leaf procedure. When no contacts were made, a spiral was started by plane No. 15, plane No. 14 continuing clover-leafs.

On fourth turn of spiral, contact was reestablished by plane No. 15 approximately 1½ miles southeast of point of losing original contact. Clover-leaf tracking followed—plane No. 14 joining as soon as plane No. 15 had positive contact. The pilot of plane No. 15 went in on bombing run, bombed at 16:55—position 35° 55′ N—05° 47′ W. (Three sticks of 8—23 bombs firing.) Plane No. 14 was approximately 300 yards behind plane No. 15. The DD fired Y gun pattern of approximately 10 depth charges, thirty seconds after No. 14's attack. DD's depth charges exploded at 16:58.

No. 15 circled area and at 17:02 observed U/B breaking water—leading edge of conning tower first, then bow, then decks awash. After hanging on the bow for approximately two minutes, the U/B sank—stern first.

Chapter 5

AUTOMATIC FIRING SYSTEMS

ONE OF THE IMPORTANT problems concerning the use of the AN/ASQ-1 equipment is that of releasing ordnance to destroy an invisible target such as a submerged submarine. Hand firing after an indication is noted on the meters obviously can be inaccurate, since the time of reaction for different operators may vary considerably. Flying at 140 knots an airplane travels 237 feet in one second. During the fall and winter of 1942-1943 several equipments for the mechanical release of ordnance were developed.

The production model of a tripper circuit to be attached to a *single* AN/ASQ-1 system for automatic release of bombs or flares upon passing over a signal peak is called the CP-2/ASQ-1. It will be described later in the chapter.

5.1 THE AN/ASQ-2 DUAL AUTOMATIC SYSTEM[a]

5.1.1 Principles of Operation

Eventually the device was adopted of using *two complete MAD systems* located as far apart laterally as possible, at the wing tips of an airplane or on opposite sides of a blimp. As indicated by the sum and difference contour charts of Chapter 4, the peaks of the sum of the two signals will usually lie close to the submarine and so are useful for actuating a tripper for the automatic release of flares or bombs. (A delay circuit was included in the production system so that the ordnance might be fired at some selected time after the sum peak if desired. This was to allow for such situations as pictured in Figure 30 of Chapter 4.)

The difference of the two signals changes sign, depending on whether the aircraft is to the right or the left of the sum peak, and is therefore a useful guide to the pilot during combat maneuvers. In the field models the difference signal was displayed on a right-left indicator microammeter.

[a] Some work was also done by the Naval Ordnance Laboratory on the use of dual AN/ASQ-3 systems.[1, 2]

During the development work various schemes were tried for compounding the two signals in such a way as to obtain a quantity whose value at a peak would be independent of the submarine moment, independent of the relative heading of submarine and aircraft, and independent of the aircraft elevation, but which would always be a measure of the *lateral distance* between aircraft and submarine. The variety of the possible combat situations illustrated in Chapter 4 indicates that this is a problem of considerable difficulty. Some use was made of the ratio of the sum to the difference of the two signals.[3] Clearly the anomaly field intensity at any point is proportional to the magnitude of the resultant submarine moment, so that in a ratio of any two linear combinations of signals this factor will cancel, leaving a quantity independent of the size of the submarine moment. However the other variables are not so easily dismissed.[4]

The system finally chosen was based on a statistical study[5] of the model signals described in Chapter 4 and was designed to meet the requirements listed above in a high percentage of the cases likely to arise in combat. The circuit allows the tripper to release a bomb on a sum-signal peak only if the ratio of the two signals falls within certain limits. The following inequality must be satisfied:

$$\frac{1 - A}{1 + A} < \frac{E_2}{E_1} < \frac{1 + A}{1 - A}$$

and both E_1 and E_2 must have the same sign. No bombs will be dropped if the two signals have opposite signs. The factor A may be varied between zero and one by a rheostat called the "lateral range" control.

With 50 feet spacing between the detector elements, with the airship flying 200 feet above the submarine at 40 knots, and with the lateral range control set at its point 2 on the control panel, the statistical study indicates that the circuit in most situations will restrict the bomb release to a band whose average width is about 100 feet.

Whenever the bombing criteria are not satisfied the tripper circuit merely releases a flare on the sum peak—or at an adjustable delay time thereafter.

The tripper should not respond to the maximum of every accidental peak in the back-

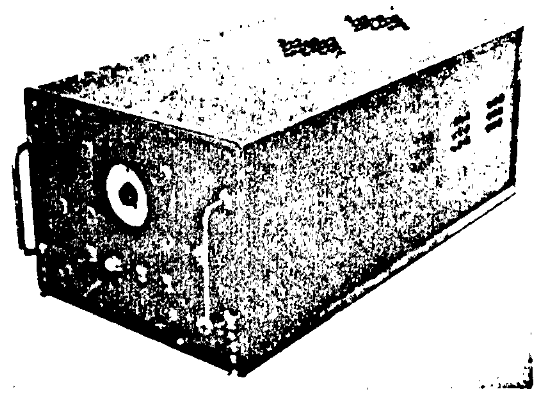


FIGURE 1. The CM-2 ASQ-2B lateral indicator and automatic tripper for use in lighter-than-air craft.

ground noise; therefore the circuit is arranged to fire on only those peaks whose maximum is above a certain *threshold* value adjustable from the control panel. It is also undesirable for the tripper to operate on those large peaks which are of geological origin or are due to violent fluctuations in the aircraft power supply, of the type seen in Figures 32 and 33 of Chapter 4. Since a true submarine signal usually has a rather distinctive shape, its harmonic analysis will usually contain a different band of frequencies from that of a spurious signal. The tripper circuit contains filters which discriminate against frequencies other than those to be expected from a submarine signal.

The complete dual automatic system is known as AN/ASQ-2. It consists of two AN/ASQ-1 or 1A units, the auxiliary unit for compounding the signals and tripping the ordnance as above described, and a test signal generator which will be taken up in Section 5.1.3. Two types of the auxiliary unit were made with different reaction times and frequency characteristics for use in lighter-than-air and heavier-than-air craft, respectively. The LTA unit is described in the next sections.

5.1.2 The CM-2/ASQ-2B Lateral Indicator and Automatic Tripper for Airships

The CM-2/ASQ-2B unit is shown in Figure 1. Figure 2 is a block diagram of its functions. The outputs of the two AN/ASQ-1 or 1A units (taken from the V106 plate circuits as usual) are fed to a balanced bridge which compounds their sum. This sum signal is sent, through a one-stage sum meter amplifying circuit, to the sum meter which is the usual Esterline-Angus recording milliammeter. Those recorders normally connected to the AM-1/ASQ-1 units are replaced by this one. The sum signal is also sent to the tripper circuit which releases either a bomb or a flare or both.

The AM-1 outputs are also sent to a bridge which responds to their difference. The sum signal and the difference signal then pass to a so-called ratio bridge. The output of this bridge

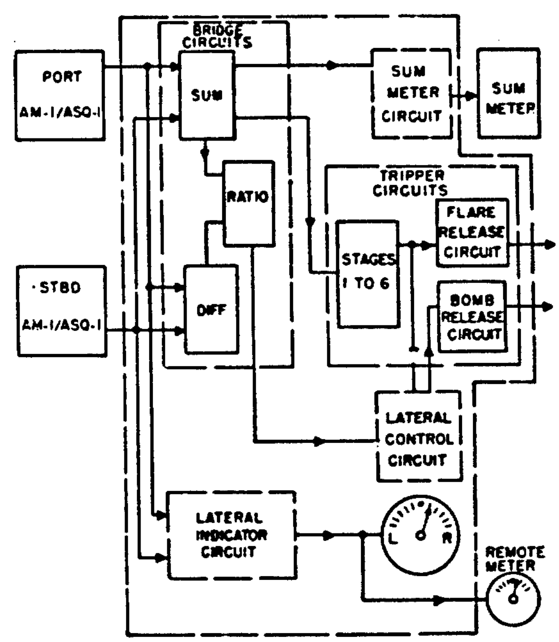


FIGURE 2. Block diagram of CM-2/ASQ-2B.

is fed through the lateral control circuit in such a way that the lateral control will not allow the tripper to release a bomb on a sum-signal peak

unless one of the relations previously listed is satisfied. The AM-1 outputs are also sent to a lateral indicator circuit which is essentially another difference-taking device. The detailed description of CM-2/ASQ-2B will be begun with the bridge circuits.

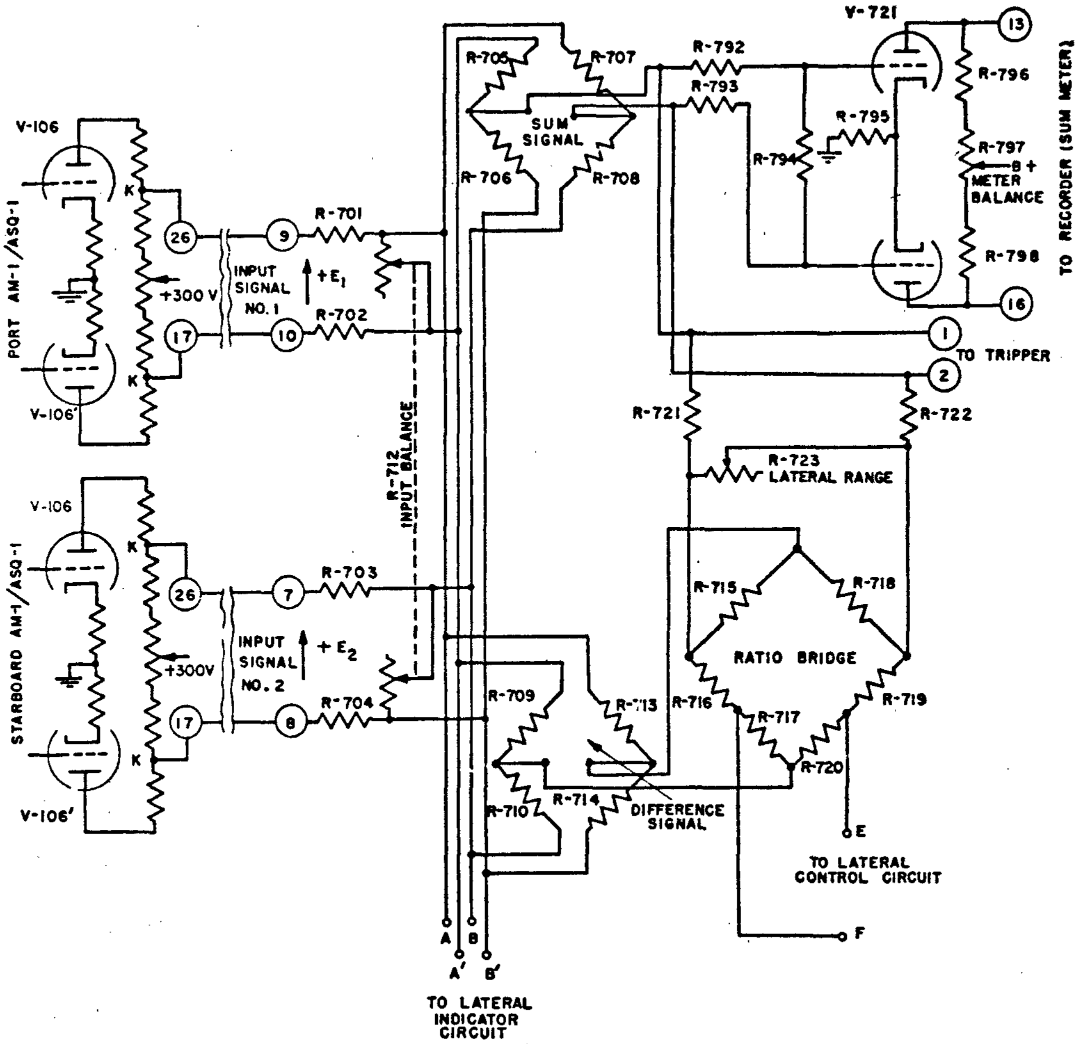


FIGURE 3. The bridge circuits and sum meter circuit of CM-2/ASQ-2B.

The Bridge Circuits and the Sum Meter Circuit

Figure 3 is a schematic wiring diagram of these sections of the unit together with the last stages of the two AM-1/ASQ-1 circuits to which it is attached. Resistor R712 is used to balance the input signals.[b] R705, R706, R707, and R708 are 0.2-megohm resistors carefully matched to within ± 2 per cent which form the four arms of the sum bridge. The bridging arm is formed by the parallel combination of the V721 input resistors, the tripper input impedance, and the resistance of the ratio bridge section. (For pur-

[b] The requirements are rather strict on equality of phase response for the two AM-1 units to be attached to this circuit. For measurements of the phase shifts produced by AM-1 at various signal frequencies, see reference 6. The requirements on stability of the sensitivities of the two units also placed added demands on the production and inspection regimes.[7-9]

poses of reference let us call input signal E_1 positive if terminal 9 is at higher potential than terminal 10, and call E_2 positive if terminal 7 is at higher potential than terminal 8.) Positive pulses from both detectors cause currents

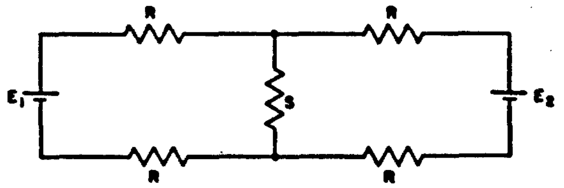


FIGURE 4. Battery circuit equivalent to sum bridge.

through the bridging arm in the same direction. The net voltage across the arm will therefore be proportional to the algebraic sum of the two signals. The effect is the same as that in the simple battery circuit of Figure 4 where the voltage across the bridging arm S is easily shown to be

$$V_S = \frac{S}{R + S}\left(\frac{E_1 + E_2}{2}\right).$$

The sum signal actuates the recorder through the V721 stage in the usual manner.

The difference bridge is so connected that pulses of the same polarity from the two detectors cause currents in opposite directions

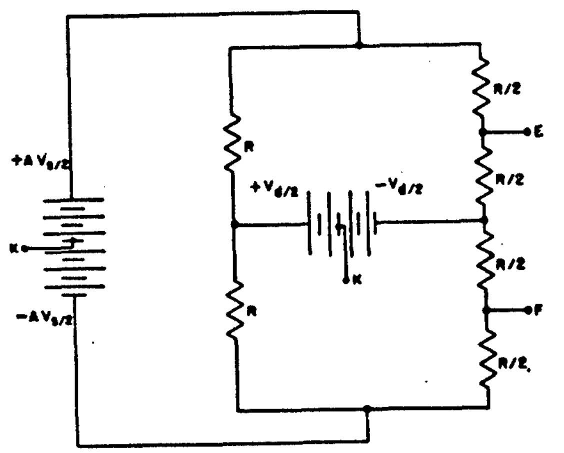


FIGURE 5. Battery circuit equivalent to ratio bridge.

through the bridging arm. The voltage across the arm, V_D, is then proportional to the algebraic difference between the signals.

As shown in Figure 3 the difference voltage is fed directly to the ratio bridge. The sum voltage is attenuated by an adjustable factor A with the potentiometer R721, R722, R723. The voltages applied to the ratio bridge are then V_D and AV_S. In the absence of signal all points of the three bridge networks rest at the potential, V_K, of the points K in the AM-1 circuits, which is about +260 volts. Any signal voltages will cause the potentials of points E and F on the ratio bridge arms to rise or fall.

The polarity and magnitude of the voltage changes at E and F, which may be called ΔV_E and ΔV_F, can be understood by comparison with the battery circuit of Figure 5. Solution of the elementary equations of this circuit gives for the potential differences between E and K, and F and K:

$$V_E - V_K = \frac{AV_S - V_D}{4}$$

$$V_F - V_K = -\left(\frac{AV_S + V_D}{4}\right).$$

Since the potential of E and F is V_K in the absence of signal ($V_S = V_D = 0$), the above expressions represent the voltage changes ΔV_E and ΔV_F required. If both input signals, E_1 and E_2, are positive, then the potential of E will rise and that of F will fall. Other combinations of input signals will cause different behavior. The explicit dependence of ΔV_E and ΔV_F on E_1 and E_2 is given by substituting in the values of V_S and V_D:

$$\frac{8\Delta V_E}{B} = E_2(1 + A) - E_1(1 - A)$$

$$\frac{8\Delta V_F}{B} = E_2(1 - A) - E_1(1 + A).$$

The extra attenuation factor B has been added to allow for the effects of the finite impedance of the sum and difference bridges. The effect of these voltage changes on the lateral control circuit is taken up in the next section.

THE LATERAL CONTROL CIRCUIT

Figure 6 is a schematic diagram of the lateral control section of CM-2/ASQ-2B. It is a dual three-stage amplifier which includes several filter networks. A *rise* in the potential of E causes a transient input signal voltage across

R799 which is amplified through the circuit so as to cause an *increase* in the V714 cathode current flowing through the relay K703. In the absence of signal, V714 is biased almost to cutoff and so K703 is open. If ΔV_E is positive and greater than some fixed amount, e volts, then the output current will be sufficient to close relay K703.

Similarly, if ΔV_F is positive and greater than e volts the relay K704 will close. Now the points I and J are so connected in the tripper circuit (to be described in a following section) that a bomb cannot be released unless there is a closed circuit in the lateral control from I to J. But the circuit from I to J will be closed if *either* K703 or K704 closes but not if both or neither of them close. One circumstance which will allow the release of a bomb is, then, $\Delta V_E > e$ and simultaneously $\Delta V_F < e$. The other case is for $\Delta V_F > e$ and $\Delta V_E < e$. Substitution of the formulas derived above for ΔV_E and ΔV_F leads to the following inequality:

$$\frac{1-A}{1+A} + \frac{8e}{B\,(1+A)\,E_1} < \frac{E_2}{E_1} < \frac{1+A}{1-A} + \frac{8e}{B\,(1-A)\,E_1},$$

provided E_1 and E_2 have the same sign. If E_1 and E_2 have opposite signs, the conditions cannot be satisfied.

This equation may be simplified by substituting $R = (1+A)/(1-A)$, to give

$$\frac{1}{R}\left(1 + \frac{4e\,(R+1)}{BE_1}\right) < \frac{E_2}{E_1} < R\left(1 + \frac{4e\,(R+1)}{BE_1R}\right).$$

The terms involving e will always be small. For example:

$$\frac{4e\,(R+1)}{BE_1R} < 0.08,$$

since $B > 0.5$, $e \approx 10$ millivolts, $E_1 > 2$ volts, and $(R+1)/R < 2$, (since $R > 1$). Neglecting these terms gives the approximate *condition for bombing:*

$$\frac{1-A}{1+A} < \frac{E_2}{E_1} < \frac{1+A}{1-A},$$

with E_1 and E_2 having the same sign at a peak. As seen from this formula, increasing A increases the allowed lateral bombing range.

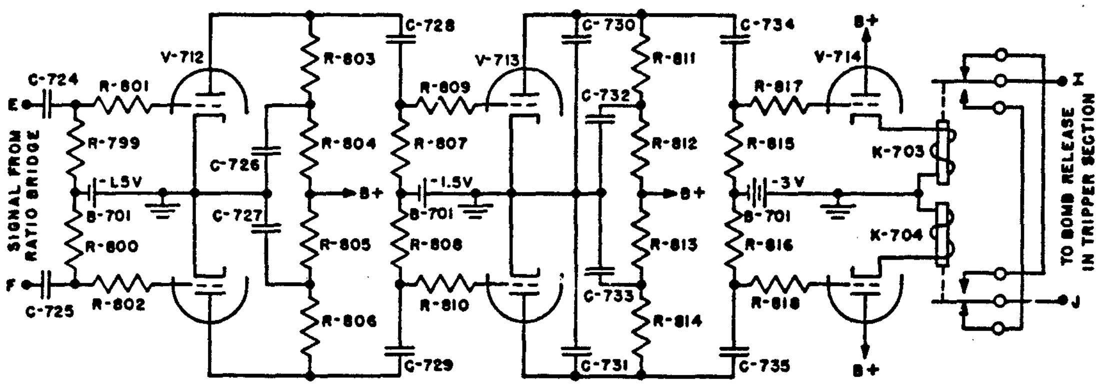


FIGURE 6. The lateral control circuit of CM-2/ASQ-2B.

THE TRIPPER CIRCUIT IN CM-2/ASQ-2B

The functions which the tripper circuit[10-12] performs are the following.

1. It rejects sum signals under a certain adjustable threshold magnitude.
2. It rejects sum signals whose chief frequency components are either too high or too low.
3. For all sum signals which are not rejected because of small size or improper frequency, it closes an external flare-dropping circuit at an adjustable time after a sum signal voltage peak of either polarity.
4. If the lateral control circuit indicates that bombs should be dropped, it also closes a bomb-dropping circuit at the same time that the flare-dropping circuit is closed.

A block diagram of this circuit is given in Figure 7. A brief and general description of the

functions of the various stages will first be given, to be followed by a detailed discussion of the operation of each stage.

The first stage, which is an amplifier of adjustable overall gain, performs the first function listed above. Eventually, at the sixth stage, the signal is required to exceed a certain magnitude. Hence, adjustment of the gain of the first stage controls the firing threshold.

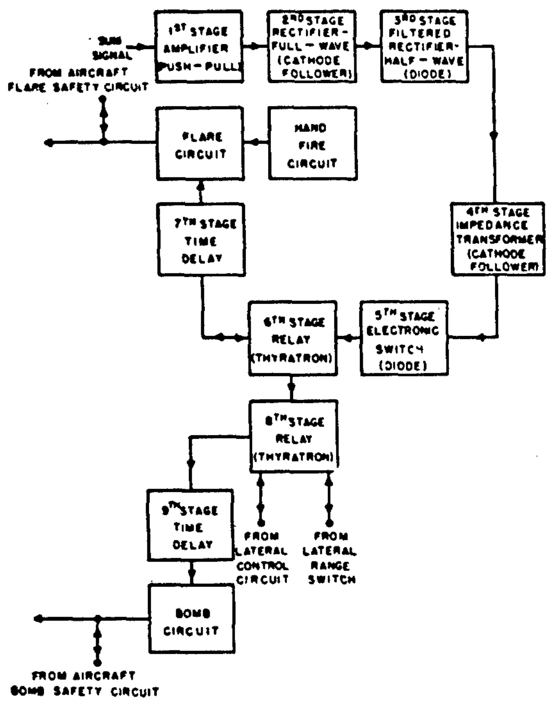


FIGURE 7. Block diagram of tripper circuit in CM-2/ASQ-2B.

The second stage, a rectifier, is required to enable the tripper to operate on signal voltage peaks of either polarity.

The third stage, a filter and rectifier stage, performs the chief part of the second function listed above; viz., that of rejecting signals having frequency components which are either too high or too low.

The fourth stage is merely an impedance transformer required to obtain a low driving impedance for the following stage.

The function of the fifth stage, called the electronic switch, is to produce a short voltage pulse as soon as possible after the occurrence of a signal voltage peak of either polarity. It is this pulse which actuates the firing circuits. Thus, the signal peak is the index point for flare or bomb dropping.

The sixth stage is a relay stage which starts the time delay circuits of the flare dropper and also passes a firing pulse to the eighth stage.

The seventh stage controls the adjustable time delay for the flare dropping mentioned as part of the third general function above.

The eighth stage is a relay stage which starts the bomb time delay circuit upon receipt of the firing pulse from the sixth stage, provided the lateral control circuit indicates that bombing should occur.

The ninth stage corresponds to the seventh stage and is always adjusted to the same delay time by a ganged control.

The reader may well wonder at the multiplicity of stages required to perform the four functions originally listed. This circuit complexity was arrived at rather empirically and was found to give the greatest possible freedom from malfunction while possessing the desired characteristics.

A detailed description of the operation of the various stages is now given.

First Stage: Amplifier. The first stage is a class A push-pull amplifier, as shown in the schematic diagram of Figure 8, which also shows the input and output wave forms. The input signal comes from the points 1 and 2 of the sum bridge. Potentiometer R726 serves as a threshold control. The time constant of the coupling circuit is from 10 to 11 seconds, and the impedance is sufficiently high so that it will not load the output stage of the AM-1/ASQ-1 units enough to cause appreciable distortion. The voltage gain of this stage is about

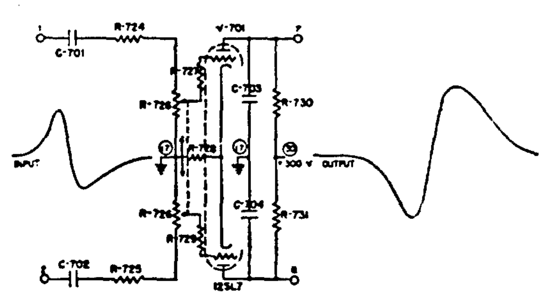


FIGURE 8. First stage of tripper unit: amplifier.

60, and the maximum undistorted output from plate to plate is about 200 volts.

Second Stage: Rectifier. The second stage is a cathode follower which acts as a rectifier. Its input circuit is a high-pass filter with a 10-second time constant which prevents distortion of the signal. A 12SL7 tube is biased beyond cutoff and is unresponsive to small noise voltages. Since the grids have opposite polarity at any instant of a signal, only one section of the tube conducts at a time; and, since the outputs are in parallel, the output signal is rectified. This stage can accept signals up to about 150 volts without distortion. A diagram of this stage, including the output-signal form is shown in Figure 9. (In these diagrams the sources of bias voltages are shown as batteries instead of the potential dividers actually used.)

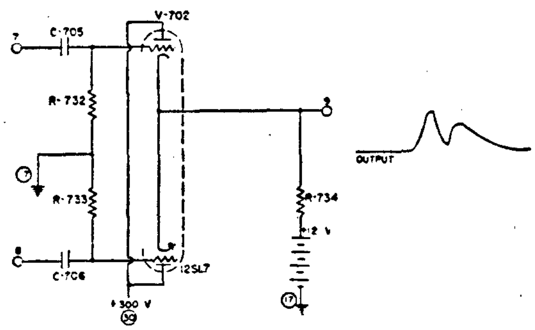


FIGURE 9. Second stage of tripper: rectifier.

Third Stage: Filter and Rectifier. The next part of the circuit, shown in Figure 10, discriminates against high- and low-frequency voltages[13] and provides a voltage difference at signal frequencies for operating the remaining tripper circuit. The input voltage at points 9 and 10 is the rectified output of the second stage. At very high frequencies, the reactances of the capacitors are negligible compared to the resistances of R739 and R740. Hence, equal voltages will appear at points 11 and 12, and the net output voltage will be very small. At very low frequencies, the reactances of the capacitors are so great that voltages appearing at points 11 and 12 will be very small. However, at signal frequencies, a larger voltage will appear at 12 than at 11, since the time constant for the path to 12 is twice that for the path to 11. (Since these time constants are too small to prevent the signal from passing without distortion, the voltages at 11 and 12 will become negative during some part of the signal duration because of the derivative-taking action of the circuit.)

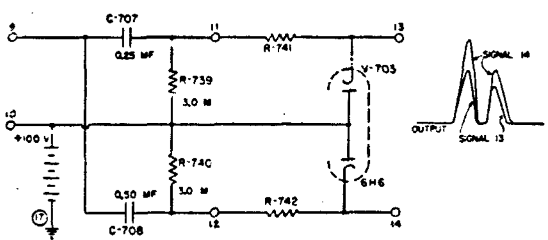


FIGURE 10. Third stage of tripper: filter and rectifier.

The frequency-discriminating network is part of the third stage which is also shown in Figure 10. This stage consists of a 6H6 diode limiter. Whenever a negative voltage appears at 11 or 12, the diodes conduct so that the voltages appearing at 13 and 14 never become negative. This rectification is essential for correct operation of the following stages. The form of the voltages at 13 and 14 is shown in the diagram. The peak at 14 is delayed with reference to the peak at 13.

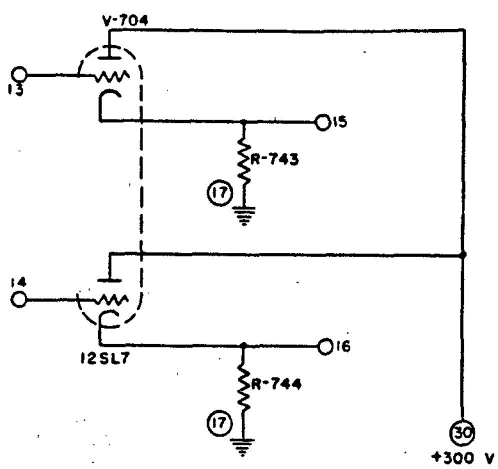


FIGURE 11. Fourth stage of tripper: impedance transformer.

Fourth Stage: Impedance Transformer. This stage, shown in Figure 11, is a cathode follower which can accept signals of as much as 100 volts without distortion. It is an impedance-

matching device which provides a high impedance for the preceding stage and a low impedance for the following stage.

Fifth Stage: Electronic Switch. A schematic diagram of the fifth stage is shown in Figure 12A while 12B is an equivalent circuit diagram

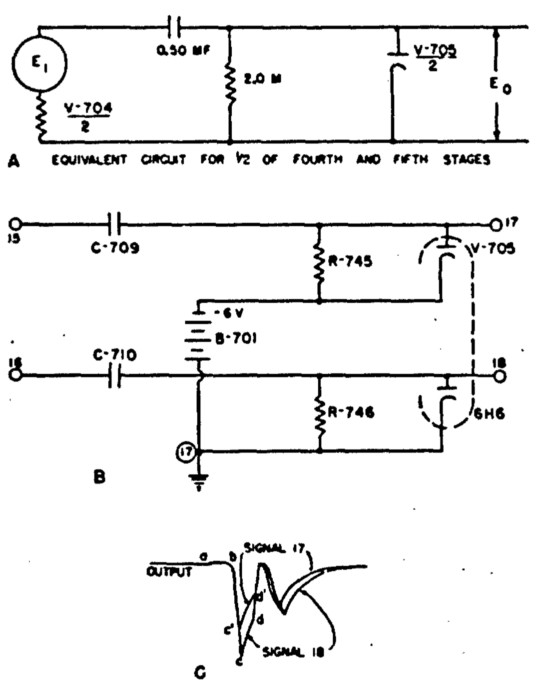


FIGURE 12. Fifth stage of tripper: electronic switch.

of one-half of the fourth and fifth stages. This diagram demonstrates the combined action of these stages in modifying the output-signal form of the third stage, shown in Figure 10, to the form shown in Figure 12C as the output of the fifth stage.

Since the fourth stage, a cathode follower, does not modify the wave form but functions simply as an impedance-matching device, it may be represented in Figure 12A as a low-impedance voltage source producing the signal voltage E_1. Also, V705 may be represented as an electronic switch, closed or conducting when the plate is slightly positive to the cathode and open when this slight positive potential is removed.

For the first part of the signal cycle, the voltage E_1 is positive and increasing, which is the necessary condition for the electron switch to be closed and the current to charge the capacitor. The drop in V705, which is the output E_0, has remained at a small positive value throughout this quarter cycle as indicated by line *ab* in Figure 12C.

During the second part of the signal cycle the voltage E_1 is decreasing from a positive maximum value to zero. The current, however, increases from zero in the opposite direction, opening the electron switch, and flowing through the 2-megohm resistor R745. The importance of this change in the path of the current is that the time constant of the circuit has been greatly increased by it, and that the output voltage E_0 is now a result of the negative voltage drop across the 2-megohm resistor, line *bc*, Figure 12C. When E_1 has reached zero, a maximum negative current flow has produced a maximum negative value for E_0. Because the RC value of the discharge circuit is longer than that of the charging circuit, there is a certain charge left in the capacitor at the time E_1 reaches zero. Therefore, since E_1 remains at zero for an interval, this charge will leak off through R745, reducing E_0 exponentially, line *cd*, Figure 12C. It should be remembered that the equivalent circuit diagram during this interval reduces to a resistor connected across a capacitor, since E_1 may be disregarded while it remains zero. When E_1

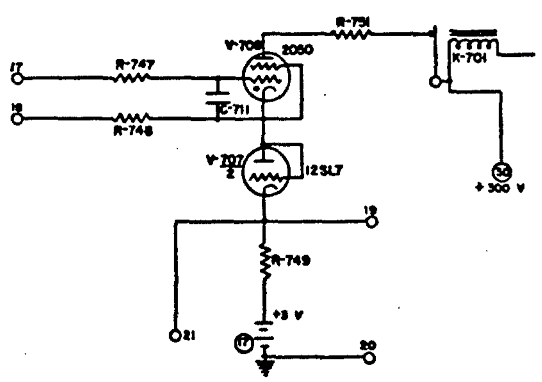


FIGURE 13. Sixth stage of tripper: relay.

again increases from zero in a positive direction, E_0 will follow until such time as the electron switch operates again.

The schematic diagram shows that the fifth stage is composed of two channels with differ-

ent input voltages which are similar to the output voltages at points 13 and 14, Figure 11. Therefore, the output voltage at 17 will reach its maximum negative value (c') ahead of the output voltage at 18 (c). This can be seen in Figure 12C by comparing curve *abcd* with *abc'd'*.

Battery B701 does not affect this stage appreciably but is used as a bias in the next stage.

Sixth Stage: Relay. The voltage at point 17 is applied to the grid of V706, while the voltage at point 18 is applied to the cathode of the same tube as shown in Figure 13. The bias battery makes the grid about 6 volts negative with respect to the cathode. When the negative signals are impressed, the grid becomes positive with respect to the cathode. If this difference voltage is enough to overcome the grid bias, the tube will "fire," but this depends upon the difference in peak values of the grid and cathode voltages, the time interval between the peak of the grid signal and the peak of the cathode signal, and the positive grid increment caused by the discharge of C709 during the time interval mentioned above. If the tube fires, it must do so during this interval, for after it the difference voltage decreases in magnitude. The difference voltage is approximately proportional to the signal amplitude as long as the capacitor, resistor, and bias values of this part of the circuit remain fixed. Therefore, the operator can determine the size of

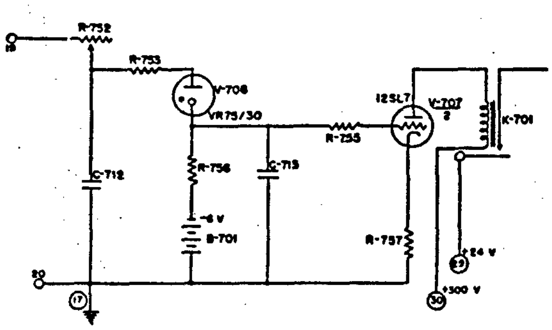


FIGURE 14. Seventh stage of tripper: time delay.

signal necessary to fire the V707 by the threshold setting of the first stage.

The diode part of V707 is in the cathode circuit of V706. Its purpose is to isolate the cathode of the thyratron until the 2050 fires. When this occurs, the cathode becomes positive enough to overcome the 3-volt diode bias which then allows the diode to conduct, and the voltage developed across resistor R749 is used as the

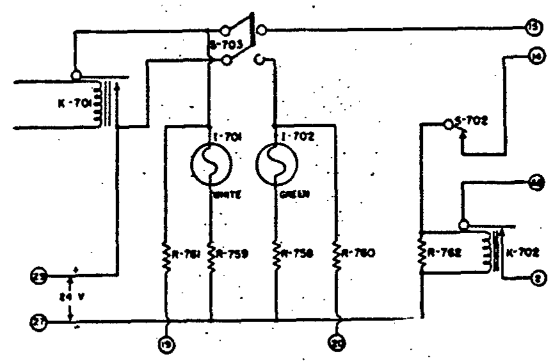


FIGURE 15. The flare circuit.

output voltage. Points 19 and 20 are the input terminals of the next stage, while *point 21 is the input terminal of the eighth stage.*

Seventh Stage: Time Delay. The last stage of the flare-release circuit is shown in Figure 14. The output signal from the preceding stage charges capacitor C712 through delay resistor R752. The value of this resistor determines the delay setting or time necessary for the capacitor to charge to the specific voltage required for V708 to conduct. When the latter conducts, it discharges C712 and charges C713 in a direction such that the grid of V707 becomes positive and the triode conducts. When this occurs, enough current, which must be more than 1.4 ma, flows through the plate circuit to operate relay K701. The contacts shown in Figure 13 open, thereby extinguishing V706, and the contacts shown in Figure 14 close, thereby operating the flare circuit shown in Figure 15.

By the time the triode has stopped conducting, causing the relay to release, V706 has stopped conducting, and its grid-to-cathode voltage has decreased sufficiently to prevent it from firing again when the plate voltage is reapplied.

Flare Circuit. When K701 operates, it closes the flare circuit shown in Figure 15. The white indicator lamp I701 is in parallel with the flare circuit, so that it lights whenever the relay

operates; i.e., whenever the detector crosses a signal peak.

If switch S703 is closed, the circuit containing the green indicator lamp I702 is closed.

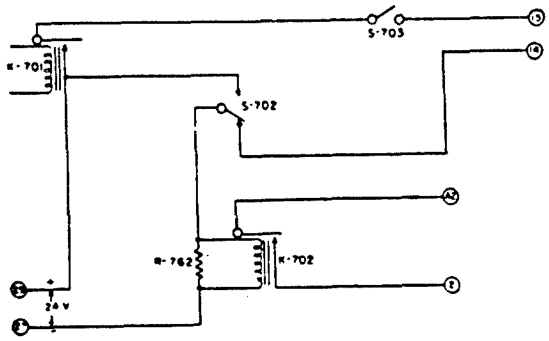


FIGURE 16. The hand fire circuit.

If the flare-safety circuit of the aircraft between terminals 14 and 15 is closed, then relay K702 will close the flare-release circuit between

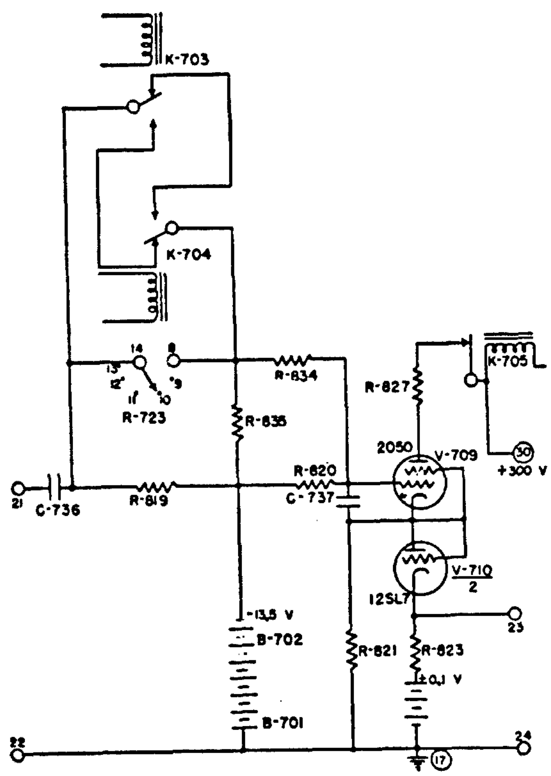


FIGURE 17. Eighth stage of tripper: relay.

terminals 2 and *A*2 whenever the white and green lamps are lighted.

Hand Fire Circuit. Figure 16 shows the hand fire circuit. When push-button switch S702 is closed, the circuit containing relay K702 is closed, and, therefore, the flare-release circuit is closed. Also, when the switch is closed the flare-safety circuit is opened This isolates the flare relay and prevents the operation of the bomb relay by means of the hand fire switch.

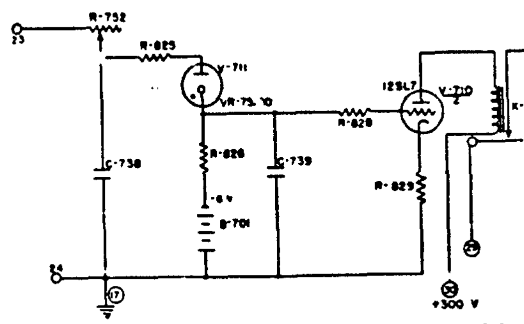


FIGURE 18. Ninth stage of tripper: time delay.

The only requirement for closing the flare-relay circuit by means of the push button is that the main ASQ power switch be on.

Eighth Stage: Relay. The eighth stage of the tripper circuit is shown in Figure 17. Point 21 is connected to the cathode of the diode section of V707. Therefore, the input voltage between 21 and circuit ground, point 22, is not the modified input signal but is a pulse that results when

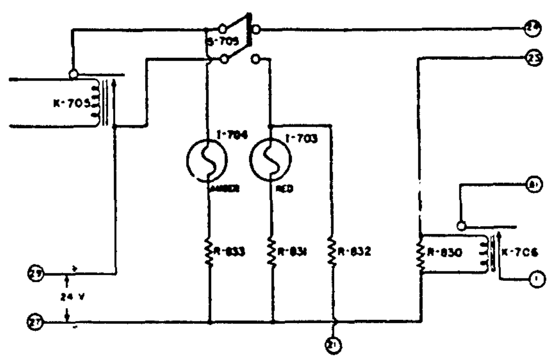


FIGURE 19. The bomb circuit.

V706 fires. It is approximately a square wave of duration equal to the delay set by the control. If neither of relays K703 and K704 is closed, and if lateral range control switch R723 is not set on "Inf." (position 8 in diagram), then the voltage pulse at 21 will pass through

the d-c blocking capacitor and filter resistor R819 to ground. The R723 shown here is a switch mounted on the same shaft as the potentiometer R723 shown in Figure 3. If either, but not both, of the relays is closed or if R723 is set to position 8, then R819 is shorted and the signal is applied to the voltage divider, R834 and voltage developed across R749 of the sixth stage.

Ninth Stage: Time Delay. The last stage of the bomb-release circuit, Figure 18, is similar to the last stage of the flare-release circuit. The corresponding component parts of the two circuits perform the same functions, so that

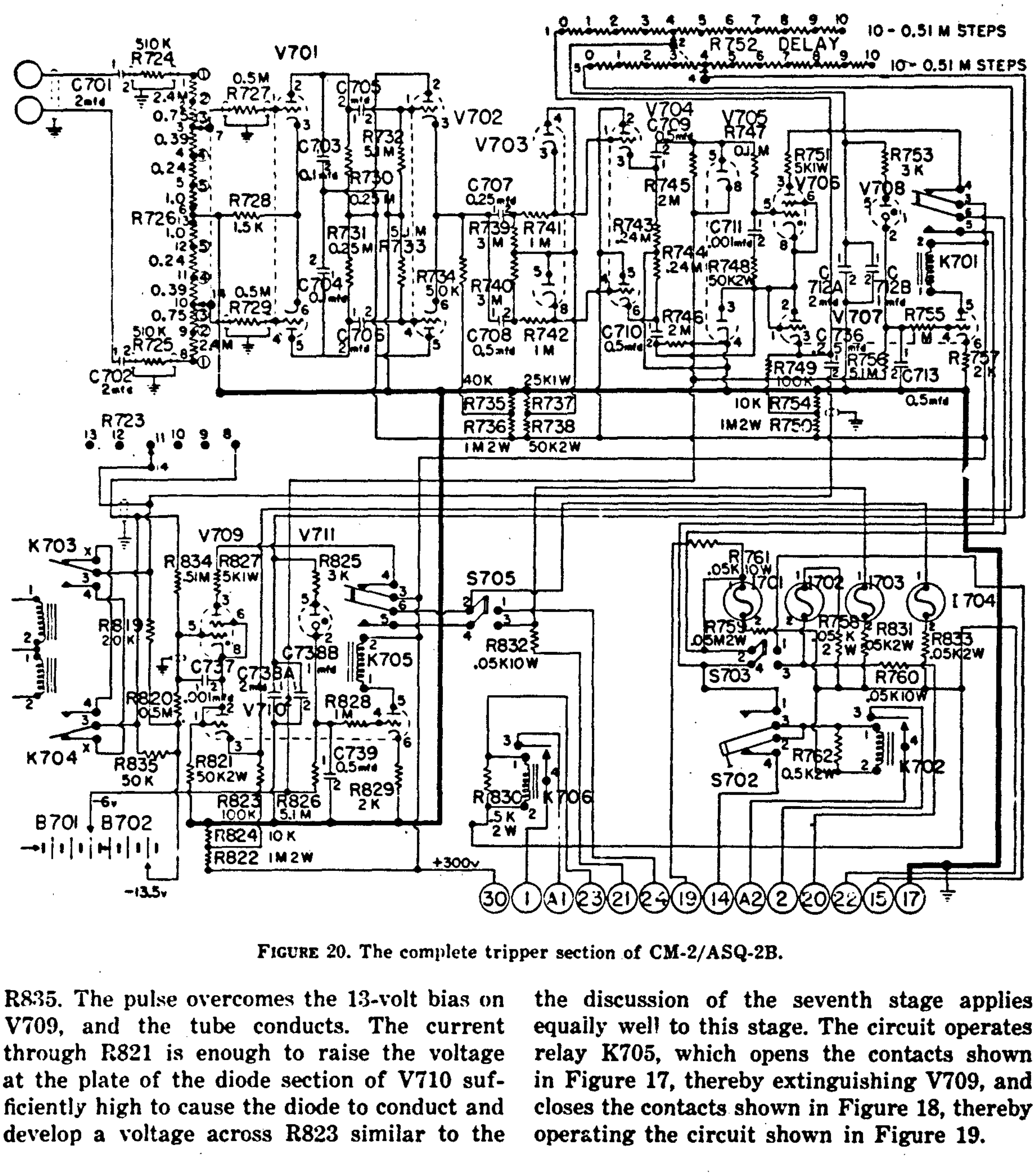


FIGURE 20. The complete tripper section of CM-2/ASQ-2B.

R835. The pulse overcomes the 13-volt bias on V709, and the tube conducts. The current through R821 is enough to raise the voltage at the plate of the diode section of V710 sufficiently high to cause the diode to conduct and develop a voltage across R823 similar to the the discussion of the seventh stage applies equally well to this stage. The circuit operates relay K705, which opens the contacts shown in Figure 17, thereby extinguishing V709, and closes the contacts shown in Figure 18, thereby operating the circuit shown in Figure 19.

Bomb Circuit. When K705 operates, it closes the bomb circuit which is similar to the flare circuit and is shown in Figure 19. Terminals 23 and 24 lead to the aircraft bomb safety circuit.

Figure 20 is the schematic diagram of the complete tripper section.

rectified. The plates are normally at –1.5 volts.

The principal parts of the last stage are a shorting switch S704, two variable-mu pentodes V719 and V720, a meter-balancing potentiometer R790, and an output lateral-indicator meter M701. The input coupling circuit is a low-pass filter with a four-second time constant. With

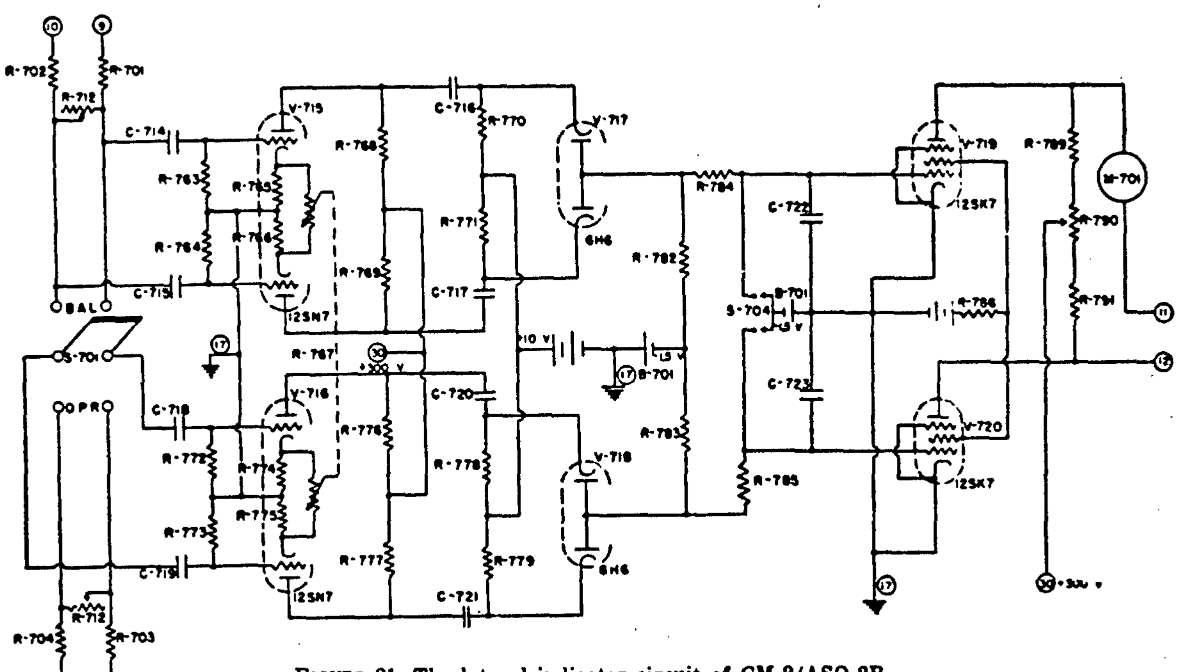


FIGURE 21. The lateral indicator circuit of CM-2/ASQ-2B.

R-782: 2.0 megohms
R-783: 2.0 megohms
R-784: 1.0 megohm
R-785: 1.0 megohm
C-722: 4.0 μf
C-723: 4.0 μf

The last part of the circuit to be discussed is the lateral indicator, which is the subject of the next sections.

The Lateral Indicator Circuit

Figure 21 is the schematic diagram of this circuit. The first stage consists of two class A push-pull amplifiers. When switch S701 is set on the OPR position, one tube amplifies the signals from one AM-1/ASQ-1 detector, and the other tube amplifies the signals from the other detector. Rheostat R767 is called "Lat. Ind. Bal." on the panel and is used to balance the two circuits when they have the same input signal if S701 is set to the position marked "Bal." The second stage consists of two full-wave rectifiers, with an 11.5-volt diode bias so that small signals and random noise will not be normal signals, the voltage across the 4-μf capacitors remains less than 10 per cent of the voltage at the diode plates. The capacitors must discharge through 3 megohms so that the time constant is well above four seconds and the meter assumes a deflection during the signal which it holds for some time after the signal has passed. Lateral reset switch S704 enables the operator to short the capacitors and return them to their original potential of –1.5 volts. This operation should be performed after every signal. By means of the potentiometer marked "meter balance" on the panel, the meter can be adjusted to give zero indication for zero signal. The output current is approximately proportional to the logarithm of the negative grid voltage. Since the lateral indicator reads the difference of the plate currents of the two

tubes, its reading is proportional to the logarithm of the ratio of the negative grid voltages. The indication for a given ratio remains constant over a range of magnitude of input voltage of six to one, falling off to zero for very large and very small signals. The pilot's indicating meter is to be connected between terminals 11 and 12.

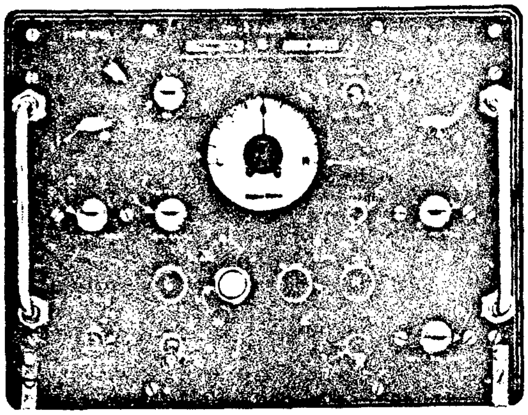


FIGURE 22. The control panel of CM-2/ASQ-2B.

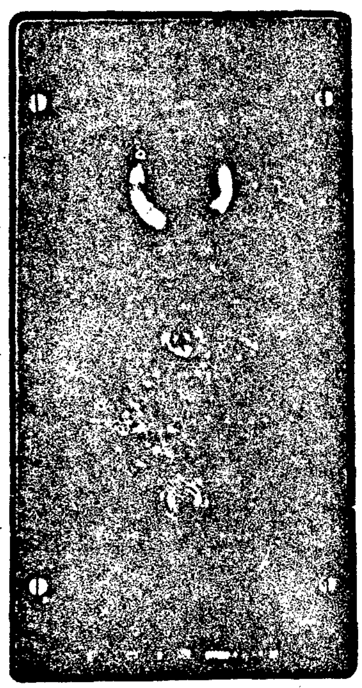


FIGURE 23. Test signal generator of CU-36/ASQ-2.

SUMMARY OF CONTROLS

As a summary of the operation of the CM-2/ASQ-2B lateral indicator and tripper unit the following list of its controls is presented. Figure 22 is a front view of the control panel with the parts numbered to agree with this list.

1. *Threshold.* This control has settings numbered from 1 to 5, corresponding approximately to the five large divisions on each side of center

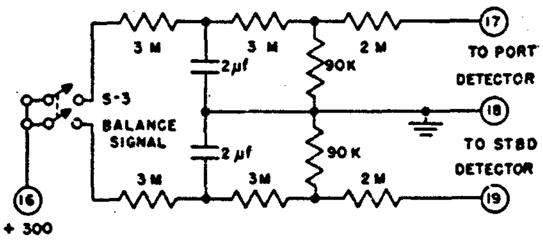


FIGURE 24. Signal generating circuit of CU-36/ASQ-2.

of the Esterline-Angus recorder. For example, with threshold set at 2, the CM-2 unit will operate the flare-release circuit whenever a signal occurs which causes a pen deflection greater than approximately two large divisions from center on the recorder tape and will also operate the bomb-release circuit if the lateral control permits. The sum meter is calibrated to give a full-scale deflection when each of the two ASQ meters gives a full-scale deflection.

The calibration of the threshold control is influenced by the condition of the bias battery B701. This battery voltage may be changed over a range from 4.5 to 6 volts to correct the calibration.

2. *Flare switch.* When this switch is set to the *On* position the flare-release circuit will be closed whenever a signal greater than the threshold amplitude occurs if the flare safety circuit is closed.

3. *Bomb switch.* When this switch is set to the *On* position the bomb-release circuit will be closed whenever a signal greater than the threshold amplitude occurs, if the lateral control permits and if the bomb safety circuit is closed.

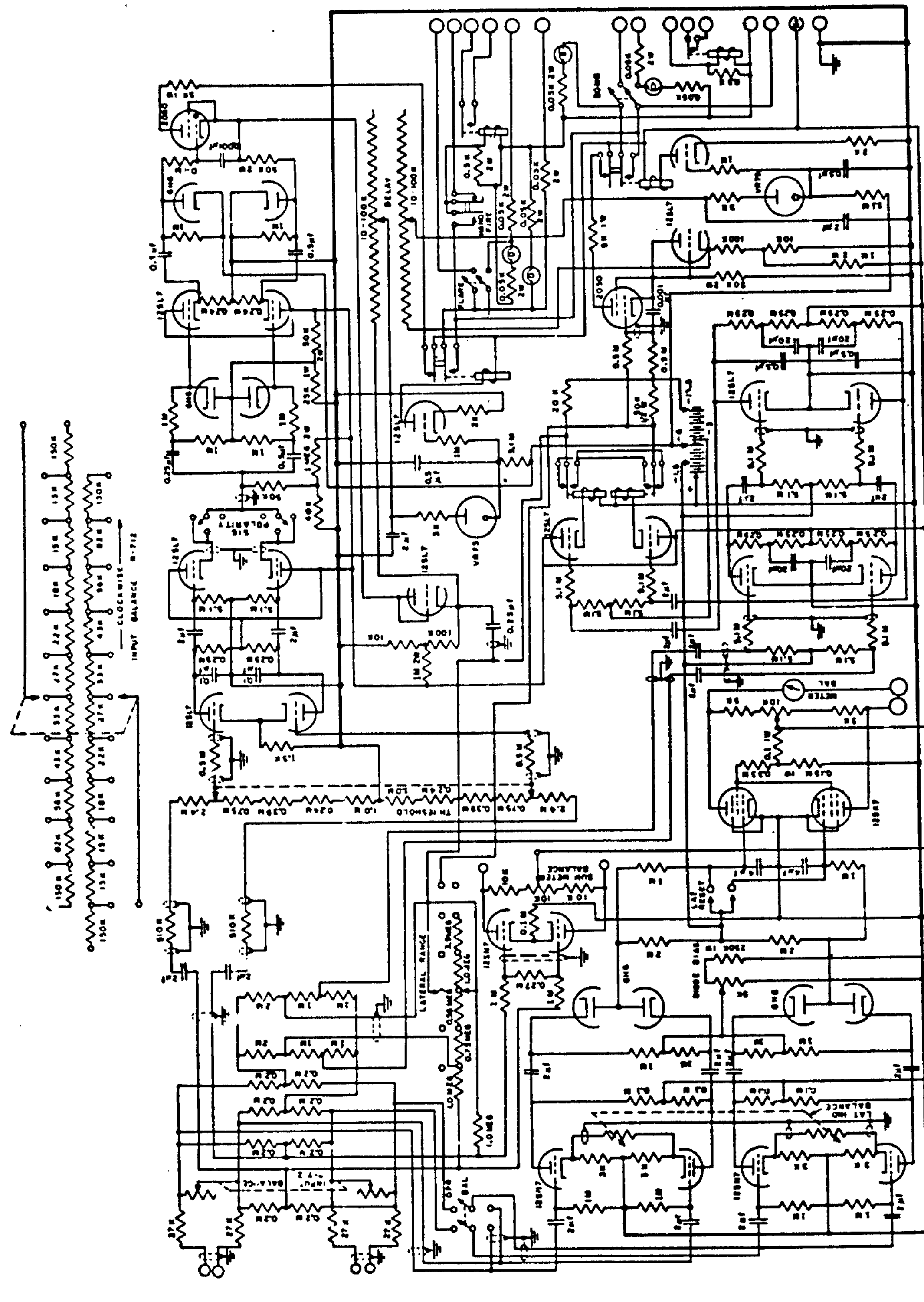


FIGURE 25. Schematic circuit diagram of lateral indicator and tripper for airplanes, CM-1/ASQ-2.

4. *Delay.* The setting of this control determines the time interval between the peak of the signal and the closing of the flare- and bomb-release circuits. The numbers 0 to 10 correspond approximately to zero to seven and a half seconds delay; that is, each division represents three-quarters of a second. The proper setting of the control depends upon the area of operation and may not be the same for flare releasing as for bomb releasing.

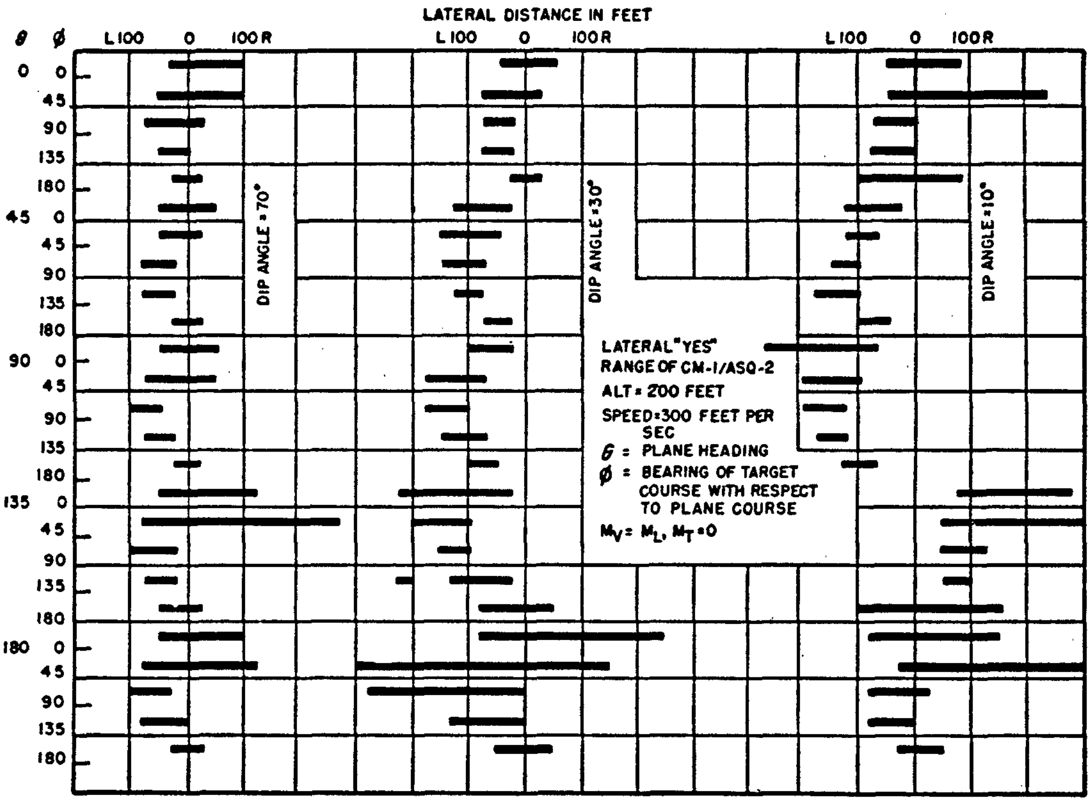


FIGURE 26. Lateral firing range of CM-1/ASQ-2 in various situations, as obtained from model signal studies.

5. *Lateral range.* The setting of this control determines the lateral limit on the operation of the bomb-release circuit.

6. *Lat. reset switch.* This switch permits quick reset of the lateral indicator meter to 0 after it has been deflected by a signal.

7. *Meter balance.* This adjustment is for initially setting the lateral indicator meter at 0.

8. *Operate bal. switch.* This switch is thrown to the *Bal.* position when the lateral indicator circuits are adjusted by the lateral indicator balance control. Otherwise it is set in the operate position.

9. *Lat. ind. bal.* With this control, the lateral indicator circuits in the CM-2 unit may be balanced.

10. *Input bal.* This control is used to balance the outputs of the two ASQ equipments.

11. *Hand fire switch.* Whenever this push-button switch is depressed, the flare-release circuit is closed regardless of the setting of the flare switch, bomb switch, threshold control, or of continuity in the flare safety circuit, if the main ASQ power switch is turned on.

12. *Sum bal.* This control is used to bring the pen of the sum recorder to center scale when the CM-2 unit is initially adjusted after the power is turned on.

13. *Indicator lights.* The CM-2 panel contains four pilot lamps. The green flare ready lamp

(*G*) burns continuously when the flare switch is set to the *On* position. The red bomb ready lamp (*R*) burns continuously when the bomb switch is set to the *On* position. The white flare relay (*W*) burns for about five seconds every time a signal greater than threshold amplitude occurs, regardless of the positions of the bomb and flare switches. The lighting of this lamp indicates that the sensitive relay, K701, has closed and that a flare will be released if the flare switch is *On* and the flare safety circuit is closed. The amber bomb relay lamp (*A*) burns for about five seconds every time a signal greater than threshold amplitude occurs, regardless of the positions of the bomb and flare switches, providing that the target is within the lateral range determined by the setting of the lateral range control. The lighting of this lamp indicates that the sensitive relay, K705, has closed and that a bomb will be released if the bomb switch is on and the bomb safety circuit is closed. Bomb and flare switches must not be turned from off to on while relay lamps are lighted since this will cause bombs and flares to be released.

8.1.3 Test Signal Generator

This unit, which is shown in Figure 23, is a part of the standard AN/ASQ-2 dual installation. It contains (1) a switch which enables the operator to connect the recording meter either to the port detector, to the starboard detector, or to the sum meter circuit of the CM-2 unit; (2) a switch which enables the operator to turn the pilot's remote meter on or off; and (3) a push-button switch which enables the operator to produce a signal which can be used to balance the two ASQ sets and the CM-2 unit. Figure 24 is a diagram of the signal generating circuit. A more elaborate signal generator, called TS-160/ASQ-2, was also used in laboratory testing of CM-2 units.

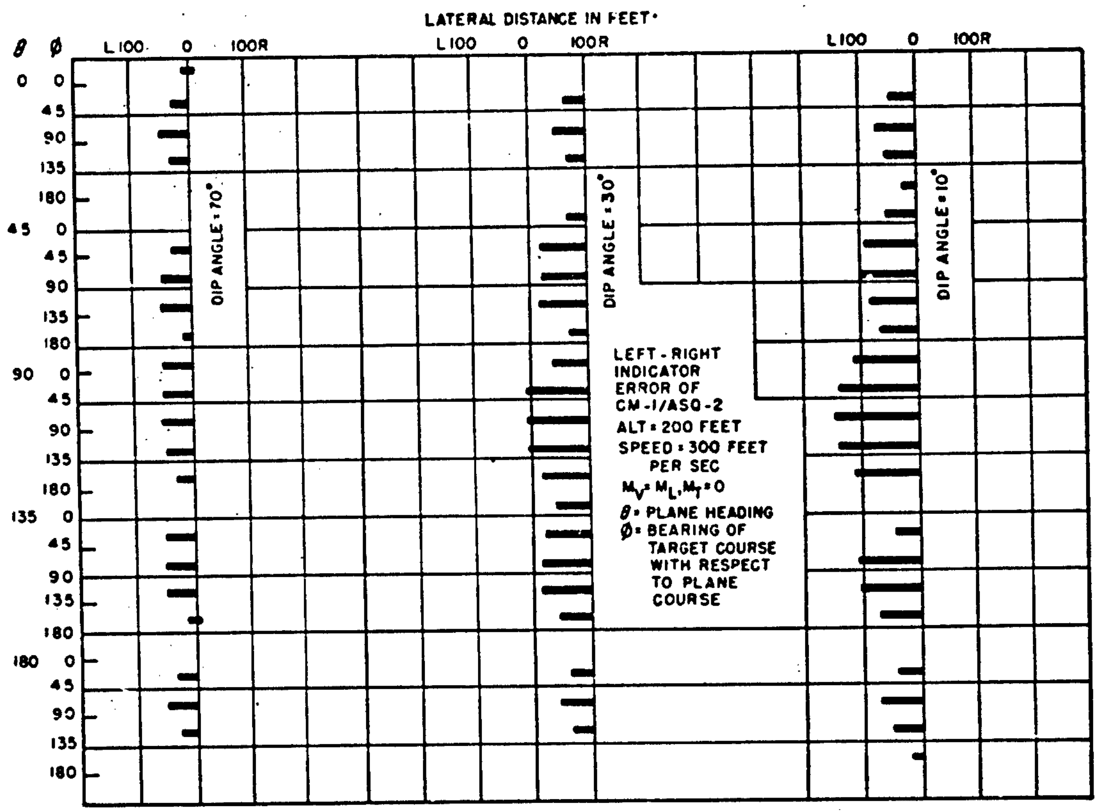


FIGURE 27. Left-right indicator error of CM-1/ASQ-2.

5.1.4 The Lateral Indicator and Tripper for Airplanes

As mentioned earlier in this chapter, a separate lateral indicator and tripper unit similar to CM-2 was constructed for use in heavier-than-air installations. Its circuit constants were adjusted to the higher range of signal frequencies to be expected from detectors carried in airplanes instead of blimps and to the greater lateral separation of the two magnetometer heads possible on the airplane. Otherwise its construction and operation were identical to the CM-2. This unit was labeled CM-1/ASQ-2; its circuit diagram is given in Figure 25.

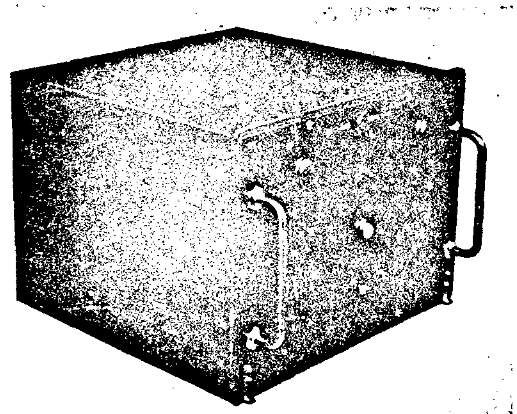


FIGURE 28. Automatic tripper for single MAD systems, CP-2/ASQ-1.

5.1.5 Performance Characteristics of the Dual Automatic System

Very little actual operating experience with these dual systems was obtained during the war.[14-16] A number of model signal studies were made, from which Figures 26 and 27 show some results. The indications are that while the system is workable it cannot be expected to fire correctly every time, because of the broad range of the field variables which may occur in combat.

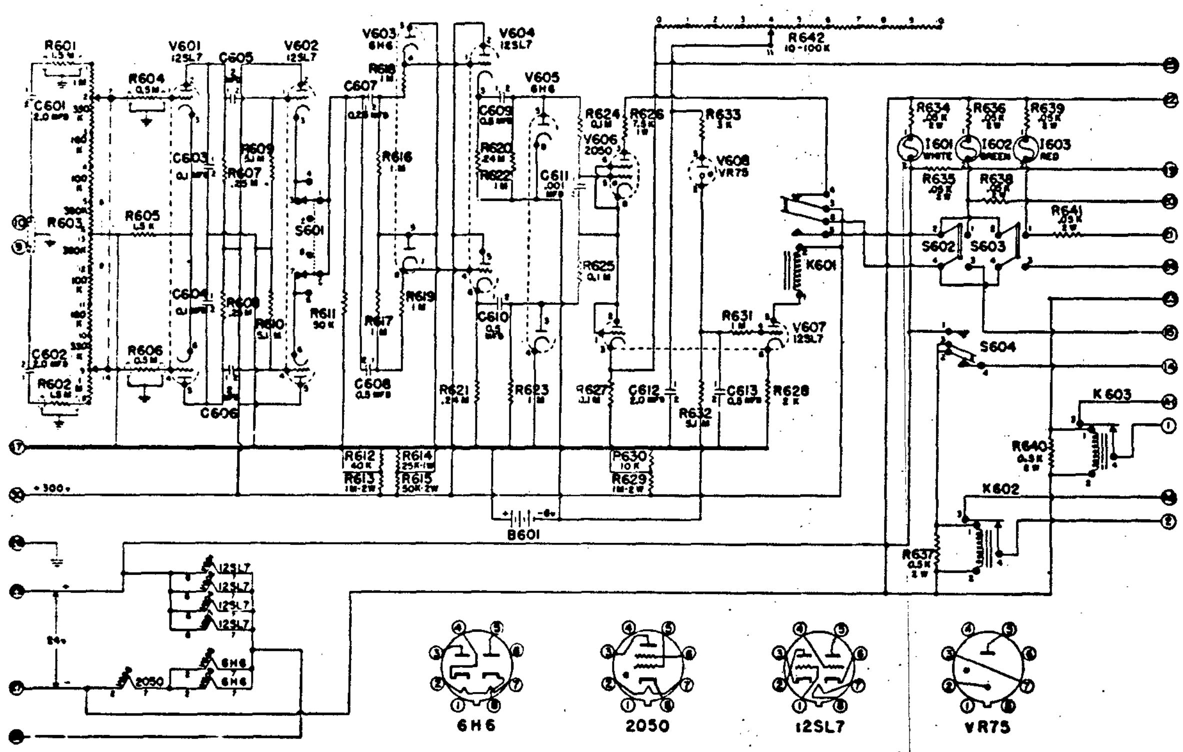


FIGURE 29. Circuit diagram for CP-2/ASQ-1 tripper.

3.3 AUTOMATIC TRIPPER FOR SINGLE MAD SYSTEMS

As stated at the beginning of this chapter, a tripper unit was also built for automatic release of retro-fired ordnance at the peak of a single MAD signal. A number of these were put in service. The unit,[17] called CP-2/ASQ-1, is shown in Figure 28, and its schematic wiring diagram is given in Figure 29. The circuit and its method of operation are practically identical with the tripper section of CM-2 already described—except, of course, for the absence of the lateral control restriction on bomb release.

Chapter 6

INSTALLATIONS OF MAD IN AIRCRAFT

When the magnetic detector of an ASQ installation is located near, or fastened to, the aircraft, spurious indications are usually recorded during maneuvers, of which Figure 1 is a sample. These indications are caused by the presence of (1) permanent and (2) induced magnetic fields at the detector which arise from ferromagnetic members of the aircraft and (3) magnetic fields set up by eddy currents generated in the conducting sheets and structures of the aircraft by the maneuvers.[a] If such in-

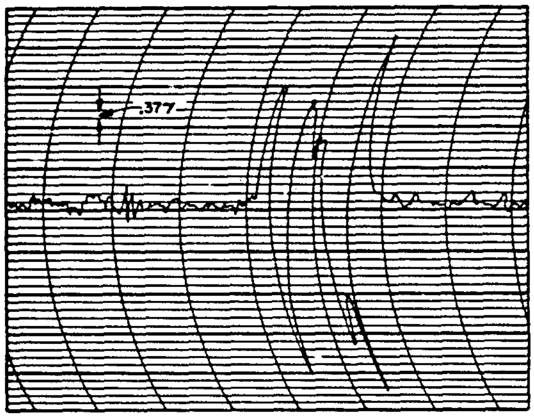


FIGURE 1. Maneuver noise from 360-degree turn in uncompensated plane.

dications are large, they may mask the signal from the target. Two methods of attack on this problem suggest themselves. One is to remove the magnetometer head from the plane and tow it behind in a suitable housing attached to the plane by a long cable. This method of the "towed bird" was carried out successfully in several laboratory installations but did not reach th field during the war. It will be discussed in Section 6.2. The method which has actually been used in service so far is to locate the head in the quietest possible position on the aircraft and then to compensate for any remaining troublesome ambient fields with properly placed permanent magnets or other devices. This compensation technique is the subject of the next sections.

[a] Of course the magnetometer head itself must have been carefully designed to avoid maneuver noise due to ferromagnetic parts and eddy-current loops in the gimbals.[1]

6.1 COMPENSATION OF MAGNETIC FIELDS IN MAD-EQUIPPED AIRCRAFT[b]

Only permanent magnetic fields were compensated at first, as induced and eddy-current effects appeared to present problems of too great complexity for the practical application of compensation procedures. In spite of this, analytical work was carried on with the hope that the disturbing fields in actual aircraft would be simpler than in the general case in which all components of the fields are assumed to be present.

Field work carried on concurrently with laboratory experiments showed that the greater part of the disturbing field is usually of a relatively simple character. It was found possible to completely compensate installations which involve the most complex magnetic fields because of the *iron* in the aircraft, provided the eddy-current effect is sufficiently simple in form. If the compensation is carried out at a single dip angle, the separation of some of the magnetic components is difficult. It may become necessary to adjust the compensation if the aircraft is flown to a location where the dip angle is more than 30° greater or less than that at which compensation was effected. In medium latitudes this may not be necessary, but for other locations it appears that the readjustment cannot be avoided if particular components are present. If the compensation procedure is carried out for an installation once at a high dip angle and again at a low dip angle, a single set of compensating factors can be found which will be valid for all latitudes.

The disturbing magnetic fields may be compensated by the use of either electronic or non-electronic devices. Both have been successfully

[b] For a more detailed discussion see references 2 and 3.

used in practice, and each method has certain advantages which must be weighed against the disadvantages for each installation. Permalloy strips and copper rings, used for nonelectronic compensation, usually extend outside the housing of the detector head and are objectionable from the standpoint of aerodynamics. However, Figure 2 illustrates a successful installation of copper rings. The use of electronic

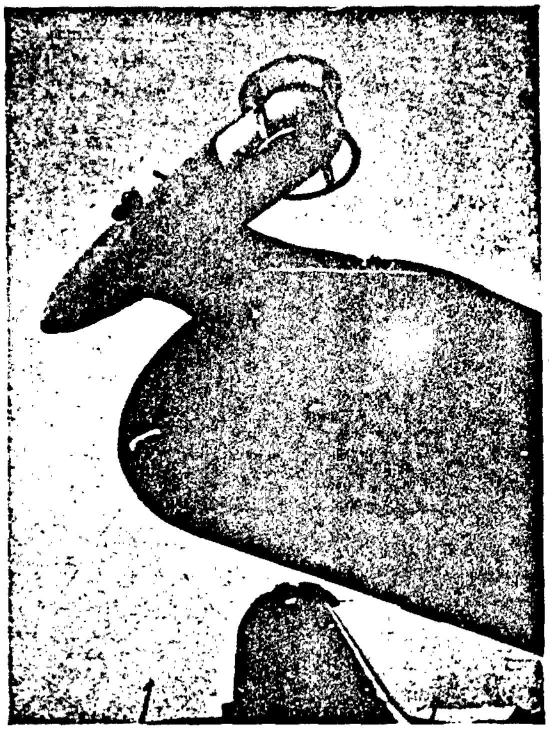


FIGURE 2. Copper rings installed outside streamlined housing.

devices increases the cost and the weight of the installation and reduces the reliability of operation. In general, it can be said that electronic compensating devices should be used only when an installation cannot satisfactorily be adapted to nonelectronic compensation.

6.1.1 Location of the MAD Head on the Aircraft

The difficulty encountered in the compensation of the disturbing fields in an aircraft depends more upon the complexity of the field geometry than upon the magnitude of the resultant indications. The most complex magnetic fields require the greatest amount of preliminary work in the analysis of the fields and the most complete compensating equipment. Consequently, the detector should be located in such a position that the complexity of the magnetic fields is minimized.

The MAD head must be placed in the aircraft in a position which is most favorable from the magnetic standpoint regardless of installation difficulties. For instance, the instrument may be less accessible for servicing, and the support for the housing may need to be heavier or may have undesirable aerodynamic properties. However, all such considerations should be subordinate to the primary objective of placing the head in the position where the equipment may function most effectively.

The installation of a single detector in an aircraft allows considerable latitude in the choice of its location. The head may be attached to any favorable portion of the wing (Figures 3 to 5) and is sometimes installed at the tail of the aircraft (Figures 6 and 7) to remove it as far as possible from disturbing parts such as the engine and the landing gear. On a blimp the head is usually placed in a blister (Figure 8). If a dual installation is to be made, there is little choice as to the general location of the detectors since they must be placed near the wing tips of an airplane to attain maximum separation between them. When a tentative location has been selected, an idea of the magnetic field at that point should be obtained. Construction diagrams of the aircraft will show the geometry of the ferromagnetic parts and will make possible a fair estimate of the types and magnitudes of the magnetic terms. Ground measurements can be used to great advantage in the choice of a favorable location.

When a detector is attached to the wing of an airplane, it is generally supported by a fairing in order to place it at some distance from the wing surfaces and struts. In this way, the effect of eddy currents is minimized. Regarding the effect of eddy currents, sufficient information is not available to permit specifying the

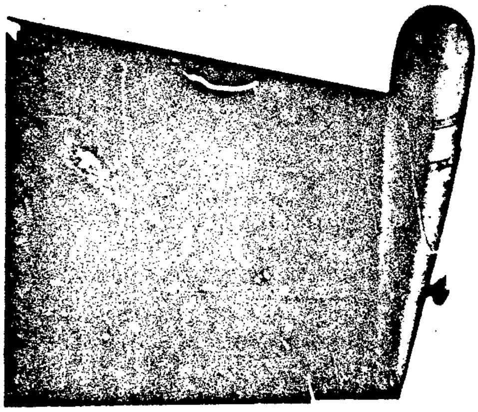


FIGURE 3. Installation on TBF wing tip.

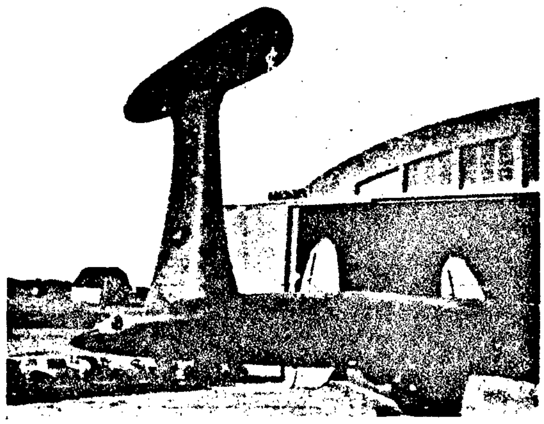


FIGURE 4. Installation on PBM wing tip, AN/ASQ-2A Starboard DT-3 unit.

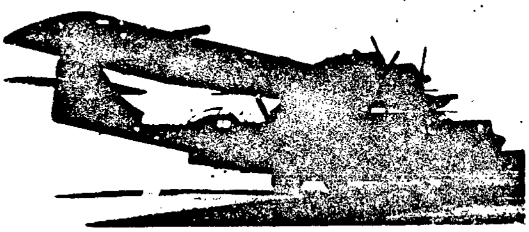


FIGURE 5. Installation on wing of PBY-5A.

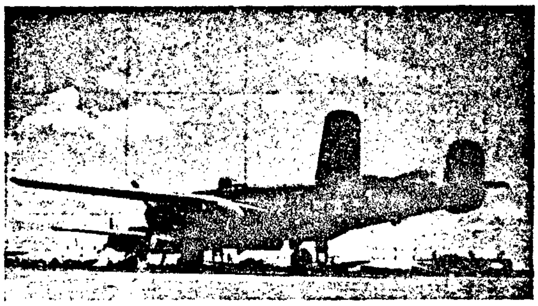


FIGURE 6. A tail cone installation.

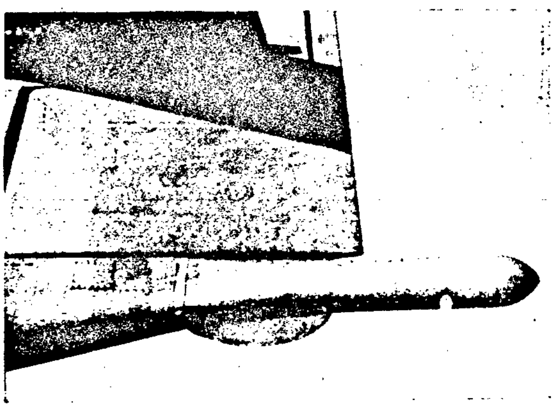


FIGURE 7. Close-up of PBY tail cone.

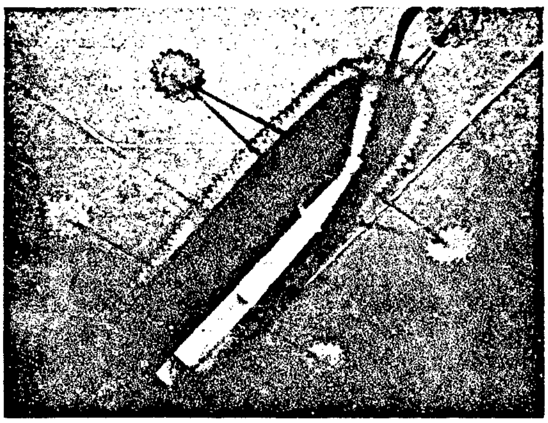


FIGURE 8. MAD blister on K-type blimp.

amount of separation of the detector from the disturbing surface which would make the eddy-current effect negligible for a particular installation. In a typical wing-tip installation for a large airplane (PBM-3C) a location of the head 3 feet above the tip of the wing gave satisfactory results. If the head were mounted

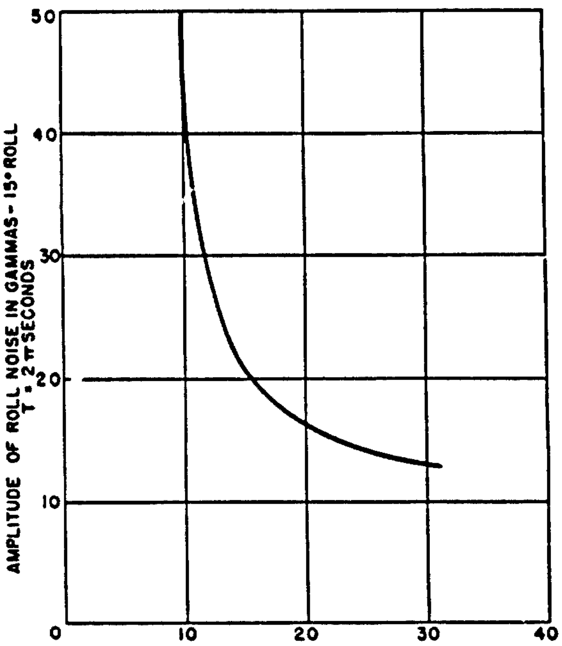


FIGURE 9. Eddy currents from PBY wing tip, 7 feet, 9 inches inboard.

over the main section of the wing, a different separation would probably be necessary. The head can also be mounted forward of the leading edge of the wing. Figure 9 shows the magnitude of the eddy-current effect as a function of the distance forward of the leading edge of a PBY-5 wing, 7 feet inboard.

6.1.2 Magnetic Components of the Disturbing Fields

Permanent and Induced Fields—Analysis[4-6]

The *permanent* field is independent of the attitude of the airplane with respect to the magnetic field of the earth. The *induced* field is a function of the attitude of the airplane.

It is convenient to resolve any disturbing field at the head into three mutually perpendicular components parallel to the natural axes of rotation of the aircraft. The longitudinal component is parallel to the fore-aft axis of the aircraft and is positive forward. The transverse component is athwartship and is positive to port. The vertical is positive downward.

The perm components along these directions are designated as L, T, and V. The permanent magnetic field resulting from any part of the aircraft may be represented by a set of three permanent magnets, giving the appropriate field at the detector in the L, T, and V directions.

The induced magnetic field from any part of the aircraft is equivalent to that of a set of three magnets parallel to the L, T, and V axes. The combined effect of all the parts can be

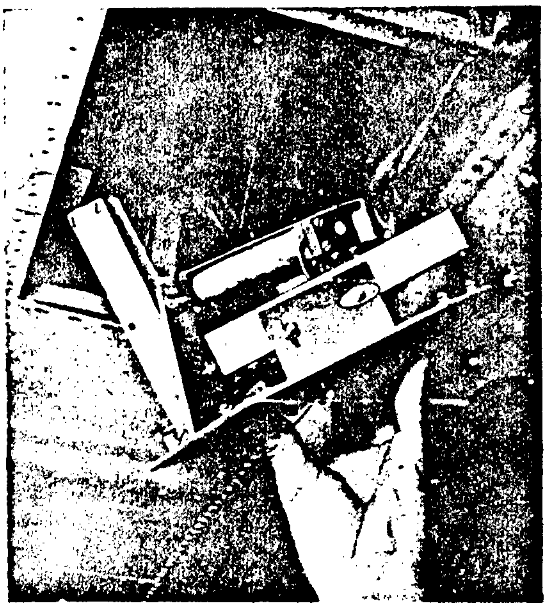


FIGURE 10. Adjustable perm compensator magnets installed in a PBY wing.

replaced, therefore, by three soft iron bars which are parallel to, but not on, the L, T, and V axes. Each of these bars produces at the head a field having components in all three directions. Thus, the total field at the detector in the L direction is equal to the sum of the L component from the bar situated in the L direction, and the L components from the T and V bars.

The components of induced magnetism are complicated, since the relationship between the components changes as the airplane changes position in the earth's field. A convenient double-letter notation has been adopted to designate induced fields at the detector. The first

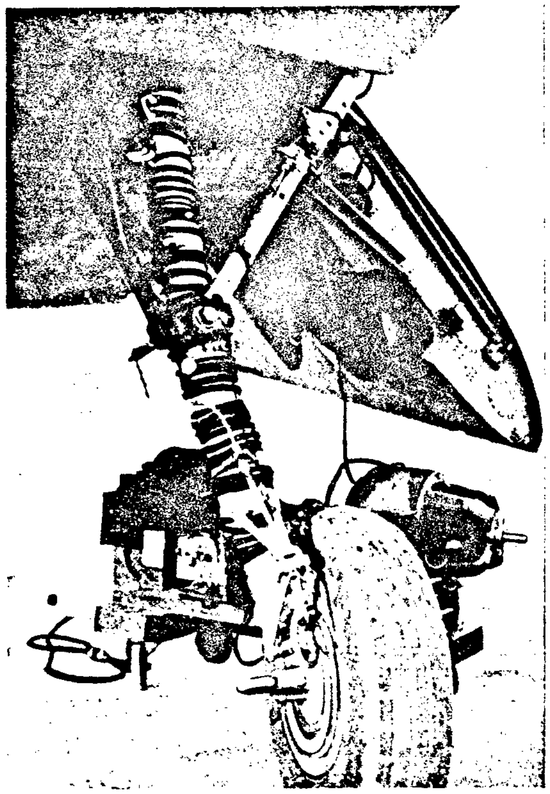


FIGURE 11. Deperming equipment.

letter stands for the direction of the source, and the second stands for the direction of the component of the magnetic field at the detector due to that source. Since the magnitude of the induced field is proportional to the value of the earth's total magnetic intensity, **H**, **H**(*TT*) designates the maximum transverse field at the detector due to an equivalent transverse soft iron bar. **H**(*TL*) is the maximum longitudinal field at the detector due to the same transverse bar. Thus, there are nine components of the induced field at the detector. Fortunately, as far as the effect on a total-intensity magnetic detector is concerned, *TL* produces the same kind of indication as *LT*; *TV* produces the same kind of indication as *VT*; and the same relationship is true for *LV* and *VL*. Furthermore, during rolls *LL* is zero; and the indications for *VV* and *TT* are of the same kind, but one is the negative of the other. During pitches *TT* is zero, and indications from the *VV* and *LL* components are of the same kind, one being the negative of the other. Therefore, it is necessary to compensate only the differences *VV* − *TT* and *VV* − *LL*. As a result, there are five components of the induced field to be considered when noise indications from the detector are being analyzed.

The three parts of the magnetic field due to perm and the five parts due to the induced magnetism of the aircraft must be compensated before maneuver noise from both perm and induced magnetic fields disappears at all dip angles.

PERMANENT AND INDUCED FIELDS—COMPENSATION[7-9]

To compensate permanent fields, one procedure consists of computing the proper values of the *L*, *T*, and *V* components from the indications obtained during test maneuvers and installing *L*, *T*, and *V* magnets to cancel these fields. This computation necessarily requires the measurement of the angles through which the aircraft is made to roll and pitch. Since it is not ordinarily convenient with this method to change the compensation in flight, several flights are usually needed to obtain the best compensation. More satisfactory results can be obtained and a considerable saving of flight time effected if an *adjustable perm compensator* is mounted near the head. This compensator consists of three electromagnets with cores of permanent magnet steel. It is located 4 to 7 feet from the detector and is oriented to give *L*, *T*, and *V* fields at the head. The magnetic moment of the cores can be altered in flight by passing a controllable magnetizing current through the proper coil and then removing the current, leaving the core with a controllable remanent magnetic moment (see Figure 10).

Another method, which may be carried out on the ground without flight tests and is often satisfactory, is to locate[10, 11] those parts of the airplane contributing to the permanent field

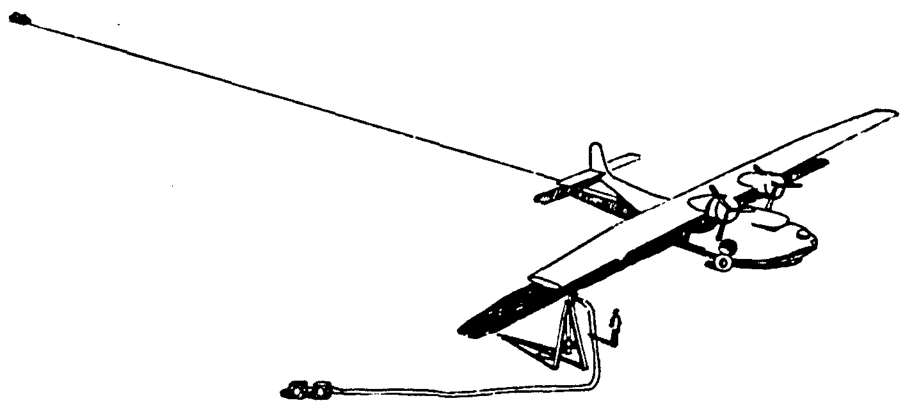


FIGURE 12. Ground measurement of magnetic components.

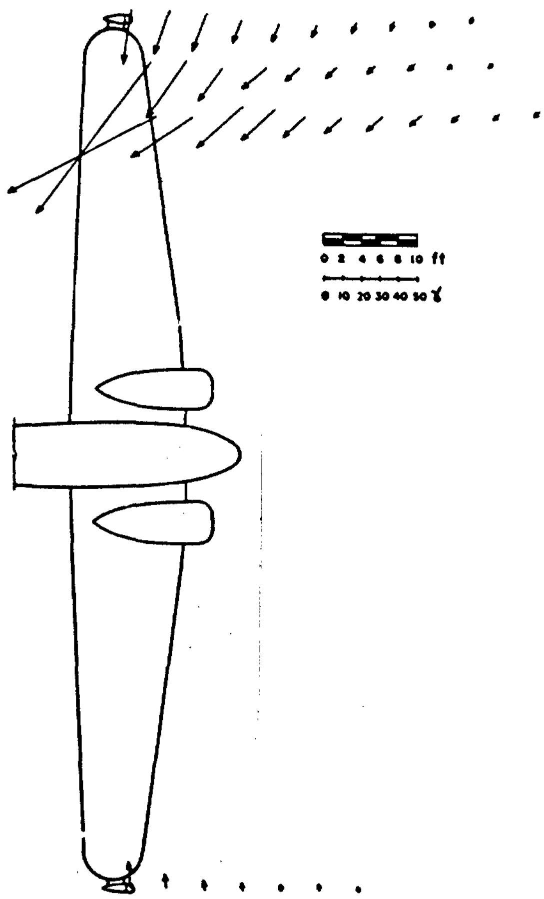


FIGURE 13. Magnetic field map for B-18. Horizontal components at wing-tip level. Measurements made with landing wheels down.

and then deperm them. The deperming may be done by surrounding the part with a coil carrying direct current which is reversed at least a dozen times while its magnitude is gradually decreased to zero. Figure 11 illustrates such an operation. Alternating-current deperming proved inadequate due to eddy currents. To measure the magnitude of the magnetic fields on the ground, a stationary magnetometer ("perm detector") is placed at the proposed position for the head; and the airplane is hauled away from the magnetometer (Figure 12). The field is measured on the four cardinal headings. The results should indicate the order of magnitude of the permanent and of the induced fields. Figures 13 and 14 show sample cases. If these measurements are carefully carried out, in a very quiet location, it is also possible to determine the magnitude of some of the elements needed for the compensation of the aircraft.[12-16]

There are two methods which may be used in neutralizing the elements of the induced field. The first method is the location of strips of Permalloy[17] in the vicinity of the detector (see Figure 15). In the second method three coils furnish the L, T, and V fields, being fed from amplified indications of three saturated-core magnetometers fastened rigidly to the airplane. This second method provides compensation which is adjustable in flight, and it has been used to measure induced fields in new installations. Its use is not recommended in Serv-

ice aircraft unless it is found impossible to achieve satisfactory compensation with Permalloy strips.

The location for the Permalloy strips is determined by the position of the equivalent member of the airplane. For example, in Figure 16, let the bar *A* represent the aerol strut as the airplane is heading west. The magnetic intensity at the head *O* due to this strut consists of components *TT* and *TL*. The component *TT* can be neutralized by a horizontal Permalloy strip *B* with its center in the *LV* plane at the proper distance from the head *O*. In practice, a convenient location for the compensating strip is aft of the head either inside the streamlined housing or fastened to the surface of the wing. The compensation of the *TL* component is not so convenient but may be effected either by the *TL* strips *C* or by the *LT* strips *D*. In the case of a wing-tip installation it is necessary to fasten the strips on an outrigger external to the streamlined housing. When strips are used in pairs like *DD* and *CC*, compensation of ten to one can be secured if the distance from the center of the strips to the center of the head is 10 inches. If an 8.5-inch diameter housing is used, the outriggers extend about 6 inches outward from the housing. Such outriggers have been successfully flown on the tail cones of Mark IV B-3-equipped PBY airplanes for the compensation of the *LT* field due to the control cables.

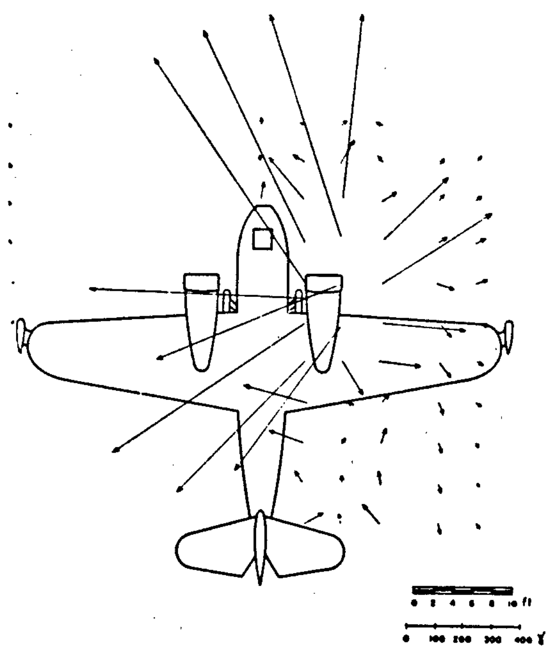


FIGURE 14. Magnetic field map for Grumman NX1604. Horizontal components 5 feet above hangar floor. Landing wheels down.

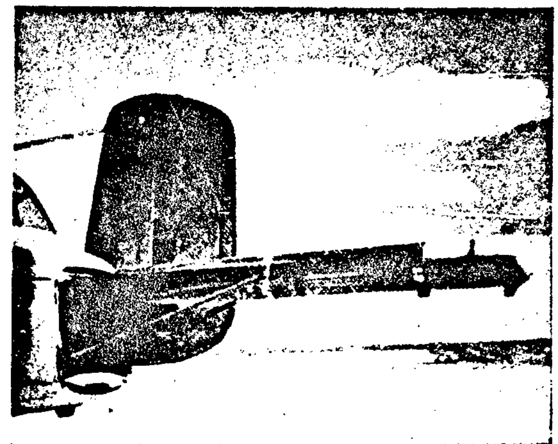


FIGURE 15. Permalloy strips mounted on fins on streamlined housing.

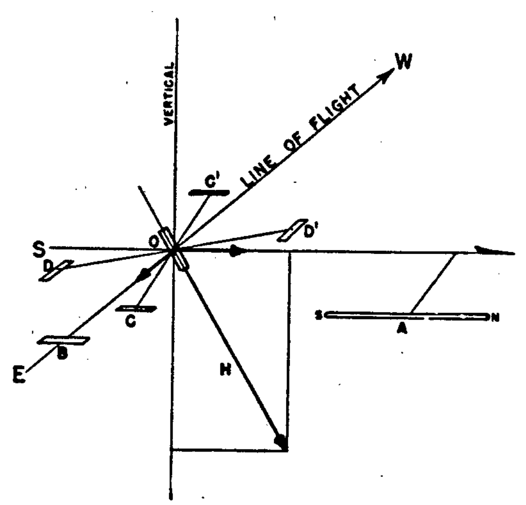


FIGURE 16. Location of compensating strips.

EDDY-CURRENT FIELDS

The eddy-current field[18-21] differs from the permanent and induced fields in that it is dependent on the time rate of change of the

orientation of the aircraft with respect to the earth's field. It is caused by eddy currents flowing in the conducting skin and structural members of the aircraft. Slow maneuvers will produce indications from the induced field, but the effect of the eddy-current field will be very small; on the other hand, the eddy-current field may be enhanced by a rapid maneuver such as a fast roll or abrupt wingup. The indication

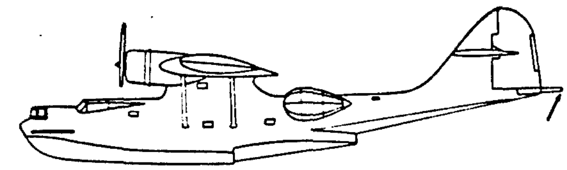


FIGURE 17. Tail cone installation in a PBY-5.

caused by the induced field depends only on the heading and the amplitude of the maneuver, while that caused by the eddy-current field depends also on the speed of the maneuver.

An analysis of eddy-current field shows that there are *nine components*. Again a double-lettered nomenclature is adopted, consistent with the manner in which the eddy-current fields are produced and detected. These nine components

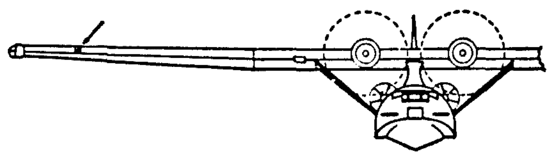


FIGURE 18. Wing-tip installation in a PBY-5.

arise from the changes in the three components of the earth's field. A change of one of the components, H_x for example, may give rise to a secondary field at the detector having X, Y, and Z components. This gives rise to the components *tt*, *tl*, and *tv*. Similarly, a change in H_y will produce components *lt*, *ll*, and *lv*; and a change in H_z will give rise to the components *vt*, *vl*, and *vv*.

At the outset it was found that eight of the nine components need to be compensated separately. The components requiring compensation may be (*vv* — *tt*), (*vv* — *ll*), *tl*, *lt*, *vl*, *lv*, *tv*, and *vt*. Although this appears to be a more complicated situation than that of the permanent and induced fields, in practice the eddy-current components are more readily identifiable. Furthermore, from the point of view of MAD requirements, only the components of the eddy-current field created by a roll or a roll-like maneuver are important, since only that type of maneuver has sufficient angular velocities to excite troublesome eddy-current indications.

Compensation of eddy-current fields has been accomplished by two methods. The nonelectronic method makes use of copper rings. An electronic eddy-current compensator has also been built. For simple eddy-current fields the copper rings are preferable because of simplicity and uniform operation. The method is limited principally by the number of components which can be supplied without the introduction of additional unwanted components. The electronic

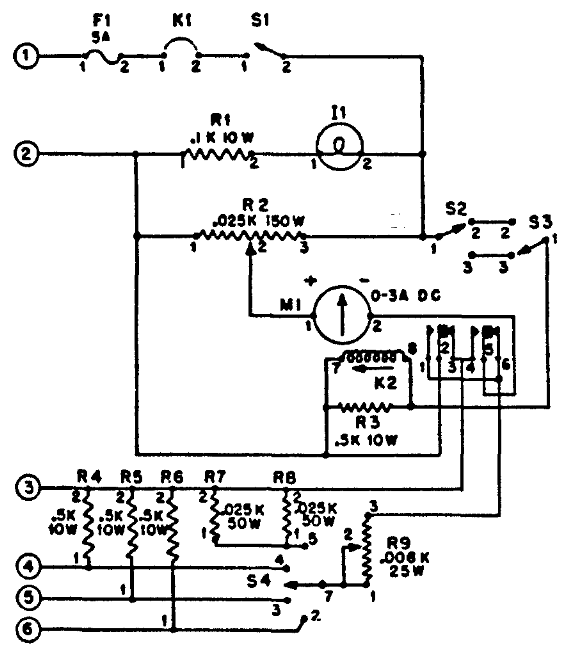


FIGURE 19. Schematic for TS-7/ASQ.

compensator does not have this limitation but may be objected to because of its complexity and the additional weight involved.

6.1.3 Compensation Flight Procedure

In selecting an area for compensation flights,[22-28] the geology of the region should be

considered since areas must be found where the magnetic gradients are small or uniform. When prospecting for a favorable location, the change of total magnetic intensity per mile should be noted on the navigation chart with the heading. Large magnetic gradients of geological origin are likely to exist where crystalline igneous rocks are outcropping or are buried at shallow

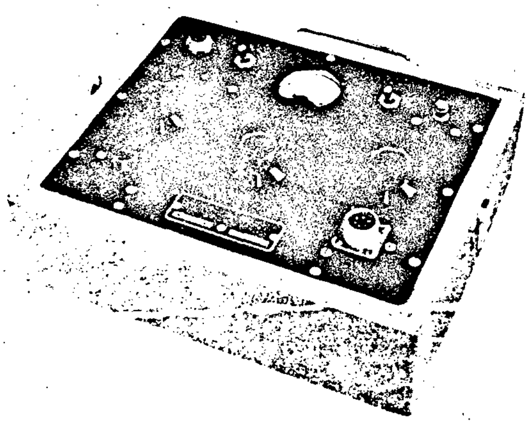


FIGURE 20. Adjustable perm compensator, TS-7/ASQ.

depths. Where sufficient area cannot be found which is free from such rocks, flights may be made over deep water, or over shallow water at an altitude of 10,000 or 12,000 feet. Near Mitchel Field, New York, a quiet region was found centering at latitude 40°19′ N, longitude 73°00′ W. If many aircraft are to be compensated from a given base, it is well worth prospecting for a quiet region because it is then unnecessary to fly at high altitudes in order to get satisfactory records.

The maneuvers used on compensation flights are rolls, pitches, wingups, and full turns. It is important that the pilot execute these maneuvers as uniformly as possible. When special equipment for the measurement of the amplitude of the maneuvers is not available, amplitude is measured by means of the flight instruments on the pilot's instrument panel. Whenever possible, the same pilot should fly the airplane until the compensation is completed, for it is then easier to compare the results from one flight to another.

An average compensation flight requires from 50 to 90 minutes depending on whether or not there are adjustable compensators on board. This does not include the time required to gain altitude, reach the starting point, and return to base. Three or four flights should be sufficient to compensate a new installation. One flight should suffice for the compensation of an additional installation in the same type of aircraft.

If the installation has been compensated by means of 15° rolls and pitches, it is well to check the compensation by violent maneuvers such as

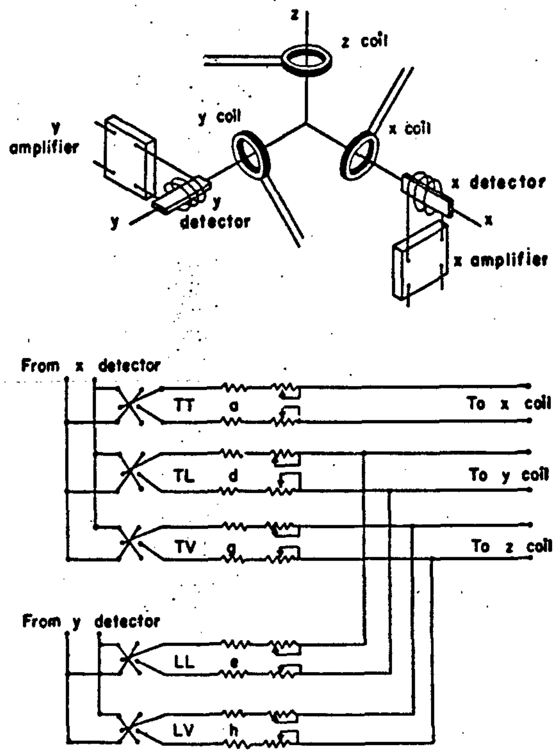


FIGURE 21. General electronic compensator for induced magnetism.

45° wingups. Small adjustments of the compensation can then be made.

Since the object of compensation is to reduce noise during tactical maneuvers, the final tests should consist of the most violent maneuvers that may be expected during the execution of a tactical problem. For these tests the recorder is connected to the regular ASQ amplifier, and the recorder tape is run at the speed of 6 inches

per minute. The clover-leaf executed at a 40° bank angle has been adopted as the ideal test because during this maneuver the aircraft goes into and out of a steep bank on four headings 90° apart. One clover-leaf is executed with left 270° turns and one with right 270° turns. The clover-leaf is started on a cardinal heading, and a straight run of about 10 seconds should be made following each 270° turn. For his record, the operator is informed by the pilot or copilot the instant the airplane is thrown into a turn, the heading at that instant, and the times at which the aircraft is on a cardinal heading. For a clover-leaf to the left, the sequence is as follows: north, west, south, east; east, north, west, south; south, east, north, west; west, south, east, north. It is sometimes useful to drop a float light on the water to insure that both right and left clover-leafs are flown over the same spot.

An indication of the complexity of the problem in the general case is given by Table 1, which is a diagrammatic representation of the sequence of operations for the identification of the various magnetic terms to be compensated and for the installation of the proper compensation equipment. These procedures presuppose that no information concerning the components is available and that it is not possible to make any assumptions regarding the components. The use of this procedure as outlined in the chart will always result in a complete and satisfactory compensation of an MAD installation. When an actual installation is attempted, however, it is soon apparent that some of the components are zero or are sufficiently small to make certain steps in the chart unnecessary. If the eddy currents are not of sufficient magnitude to be disturbing, they add no difficulty until low noise level is reached. Continuous experience with a given type of aircraft often provides a great deal of useful information on the components to be expected in the installation under consideration. Even when it is not possible actually to measure the moments of the ferromagnetic parts of the airplane, reasonable

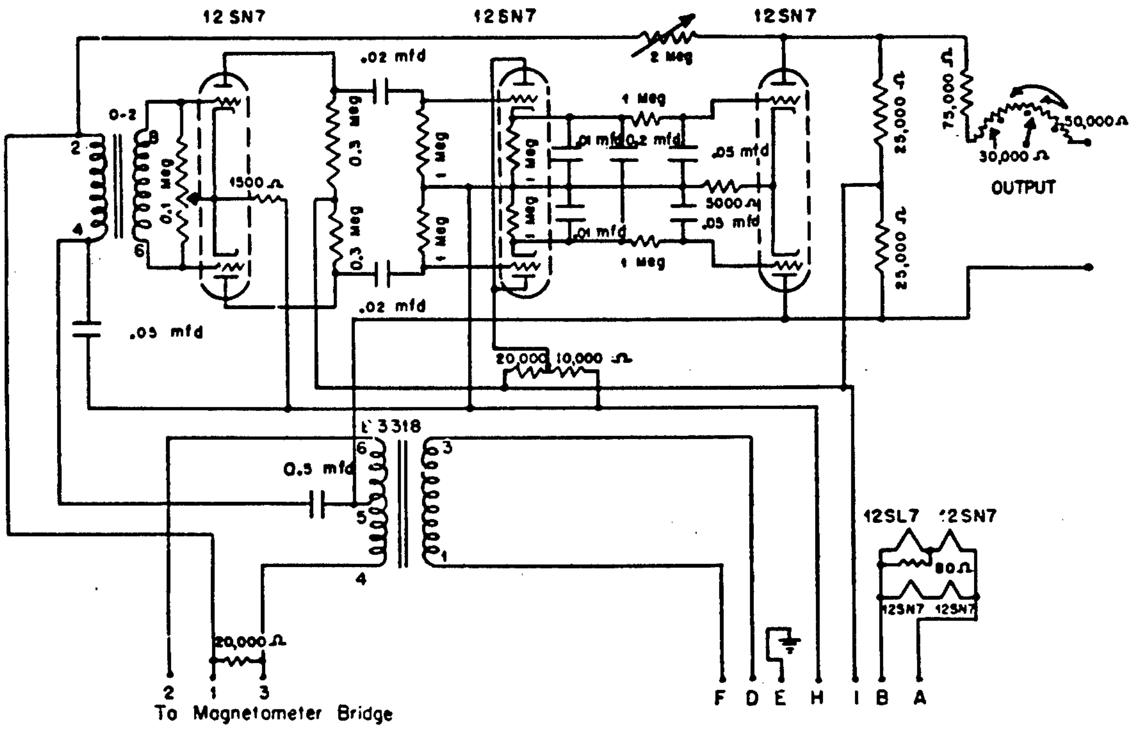


FIGURE 22. Circuit schematic of amplifier for induced field compensator.

estimates may sometimes be made of the relative strength and direction of the field which might be expected from each part.

Procedures as applied to two actual installations in aircraft are described below. In no case were ground measurements available and therefore the steps as followed correspond to the "flight measurement only" side of Table 1.

PBY TAIL-CONE INSTALLATION

Analysis. Eddy currents are not present in a tail-cone installation in a PBY since the head is far removed from any large metallic sheets (see Figure 17). All perm components may be present. *T* is probably small since the control cables to the elevators are the only transverse members near the head. *L* may be large from the control cables, and *V* may be large from the control cables to rudder and vertical sprocket chain of rudder control. The most probable source of induced field is *LL* from the control cables. Therefore, a program is built around the compensation of *LL*, *T*, *L*, and *V*.

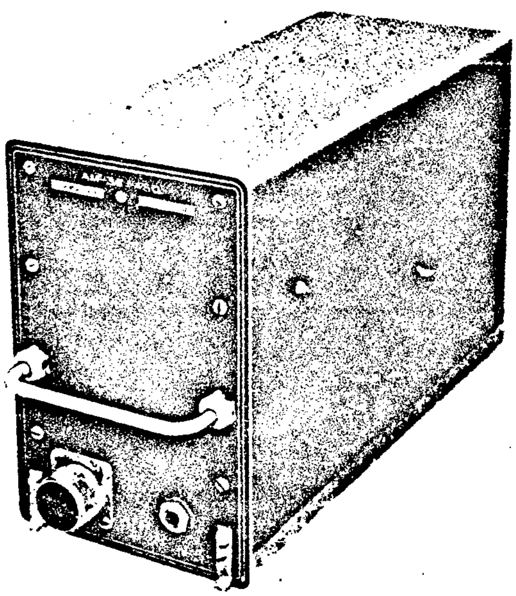


FIGURE 23. Amplifier AM-36/ASQ for eddy-current compensator.

Procedure. It was found that the simplified assumptions in regard to this installation were justified. The procedure was as follows.

1. *T* was compensated on north and south rolls by adjusting *T* until the fundamental indication was at a minimum.
2. *L* was compensated by adjusting *L* on east and west pitches until the indication was at a minimum.
3. On east and west rolls, *V* was adjusted until the indication was at a minimum.
4. Finally, by pitching on north and south and measuring the indications, the required *LL* compensation was computed and added in the form of Permalloy strips on outriggers.

PBY WING-TIP INSTALLATION

Analysis. Eddy currents in a wing-tip installation in this airplane are no doubt mainly due to extensive wing surfaces and they are probably predominantly vertical (see Figure 18). Because of the symmetry in the plane of the wings, no terms of the type of *VT*, *VL*, *TV*, *LV*, and *V* are expected. Large values of *TL*, *TT*, and *LL* are to be expected from the proximity of the wing float cross frame. Bomb racks and engines may contribute *LL* and *VV*, respectively.

Procedure. 1. The pilot installation had fixed the position of the detector along the leading edge to be 7½ feet inboard of the wing tip. The detector was experimentally placed 6 inches forward of the leading edge. The eddy currents were far too large to allow effective compensation. The detector was moved to 28 inches forward of the leading edge, at which position eddy currents were found to cause indications of 14-gamma amplitude for the standard roll. The eddy-current indication was different in magnitude on the E and W headings, indicating the presence of a transverse component of the eddy-current vector. This component is probably due to the rib structures forming closed loops in vertical-longitudinal planes. Therefore, electronic eddy-current compensation was used in this installation. An approximate correction was applied by tilting the eddy-current output coil in the proper direction to help correct for the transverse component. The total reduction of eddy-current noise was at least ten to one.

TABLE 1. Outline of compensation procedure.

USING GROUND AND FLIGHT MEASUREMENTS

Ground measurements give
TT
LL
TV
LV
TL
LT

Ground measurements do *not* give
(*a*) Separation of the components in the terms
$T + VT \sin \phi$
$L + VL \sin \phi$
$V + VV \sin \phi$
(*b*) Eddy-current components

USING FLIGHT MEASUREMENTS ONLY

IF EDDY-CURRENT COMPENSATOR IS AVAILABLE

Perform actual compensation of eddy-current components, reducing noise to pure static indications.

IF PERM COMPENSATOR IS AVAILABLE

Determine the eddy-current components by reducing static indications to zero, using T, L, and V.
Provide compensation.

All eddy currents have been eliminated.

Evaluate $TL + LT$ on north and south rolls.
Provide compensation.

Evaluate VL and VT, quieting north and south rolls with T and east and west rolls with V.
Provide compensation.

Evaluate $LV + VL$ and $TV + VT$, quieting north and south rolls with T and east and west rolls with V.
Provide compensation.

Compensate T on north and south rolls.
Measure east and west rolls.

Compensate L on east and west pitches.
Measure north and south pitches.

V, VV ← Components still to be compensated. → V, $(TT-LL)$, $(LL-VV)$

Determine V and VV with circle maneuver.
Provide compensation.

Determine V and TT with wingup maneuver on east and west headings.
Provide compensation.

Evaluate $VV-LL$ on north and south pitches.
Provide compensation.

Check flight, using right and left clover-leaf maneuvers.

2. $(TL + LT)$ was evaluated by rolling on N and S headings and making $NR = SR$. The residual was due to T. $(TL + LT)$ was compensated.

3. T was adjusted on N and S rolls until $NR = SR = 0$.

4. L was adjusted on E and W pitches until $EP = WP = 0$.

5. The indication on the E and W rolls was measured in order to evaluate TT. This compensation was installed, and indications on N and S pitches were measured for the evaluation of LL.

When the aircraft had been compensated for T, L, $(TL + LT)$, and TT, but not for LL, the full circle maneuver was flown. The turn noise was nearly pure second harmonic which is unique to LL when $(TV + VT) = 0$. This proved that the assumptions regarding the unimportance of VV and V were correct. However, because of certain limitations of expediency, LL compensation was not installed.

Squadron Results. One airplane of a squadron of 15 was used for the detailed preliminary study as described above. The values of T and $(TL + LT)$ were determined from this airplane and this amount of compensation applied to the rest of the aircraft. The values proved to be correct in all cases and the same amount of eddy-current compensation was also required for all the aircraft. The permanent magnetic field was due to the welded and magnafluxed members of the cross frame and hence was completely random from aircraft to aircraft. The values were as follows.

$(TL + LT)$	45 gammas
TT	34 gammas
T	−150 to +150 gammas
L	−200 to +200 gammas
LL	45 gammas (not provided)

The average noise level for a clover-leaf maneuver was about 5 gammas maximum excursion. It was due principally to the lack of LL compensation. However, the maneuver noise was of somewhat continuous character and not easily confused with true indications. When LL compensation was later provided, the noise level was reduced to 2.5 gammas.

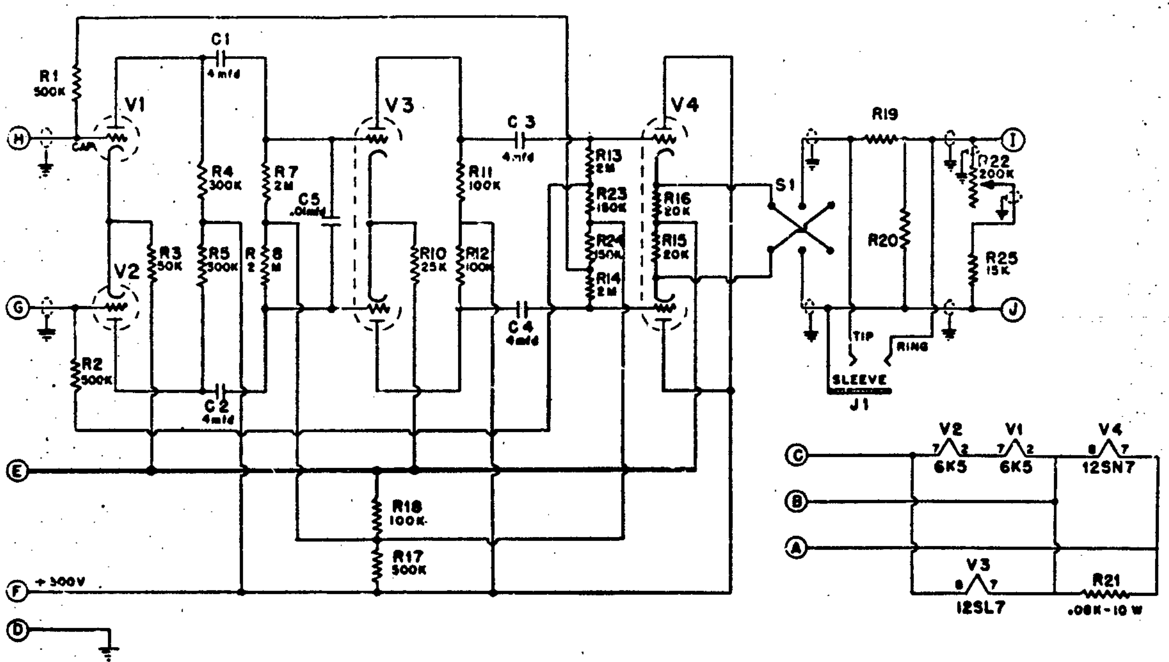


FIGURE 24. Circuit schematic of AM-36/ASQ eddy-current compensator.

SERVICE COMPENSATION

When an aircraft with its MAD installation is ready for service, it will have been compen-

sated for eddy currents and induced and permanent magnetic fields. It has been found that the induced magnetic compensation will be unchanged with service life. As yet, there is no evidence that the eddy-current compensation will require any change, but it is possible that it may. The perm in the aircraft is expected to change with length of service, though neither drastically nor often. For example, after two months of active service a squadron of PBY-5's showed negligible changes. On the other hand, a carrier-based TBF after some service has been known to show a marked deviation from original values.

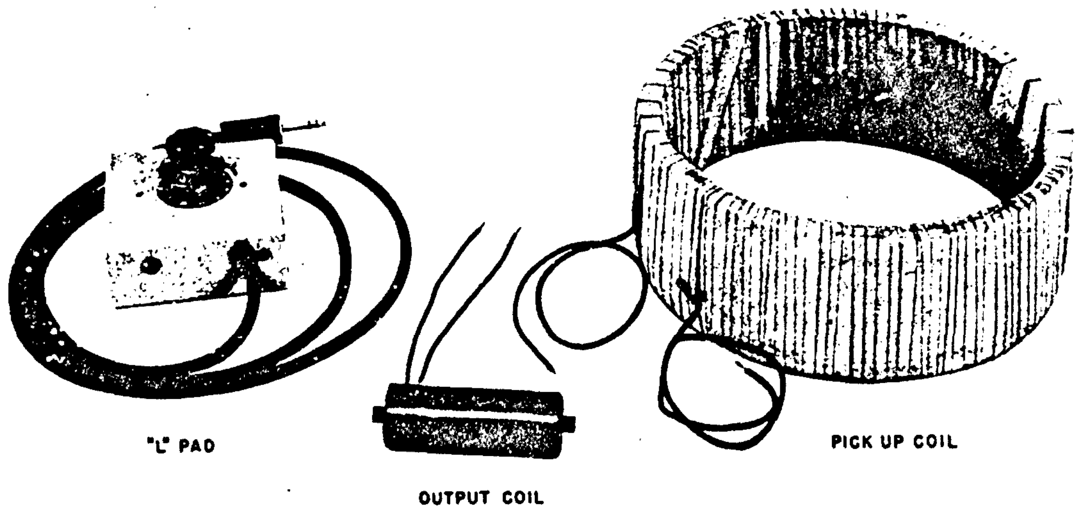


FIGURE 25. L pad and coils.

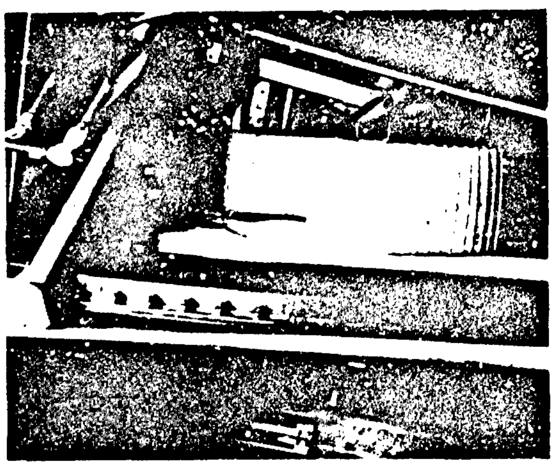


FIGURE 26. Eddy-current compensator input coil installed in a TBF wing.

Thus, it is expected that periodically the aircraft will have to be recompensated for perm and examined for evidence of eddy-current change. The procedure for such an examination and adjustment of values is quite simple. The adjustable perm compensator is the only additional equipment necessary. Without changing the magnetization of any of the coils, a record of pitches and rolls on the cardinal headings is first taken. This alone will give the operator some notion of the state of magnetic unbalance.

The examination of the aircraft for eddy currents is done on the basis of change of amplitude with change of frequency. T is adjusted until minimum noise is obtained on east heading, with a slow roll having an amplitude of 15° and a period of about 12 seconds. The roll frequency is then doubled, the amplitude remaining constant. If the indications for the fast roll are more than 50 per cent greater than those for the slow roll, there is positive evidence of need for adjustment of the eddy-current compensation. If an adjustable eddy-current

compensator is part of the installation, its gain is changed until the indication on the fast roll is less than 150 per cent of the indication on the slow roll.

Inasmuch as the operator will probably have no record of the previous magnetizing currents, he should next reduce to zero the moments of the perm magnets. The following steps will de-

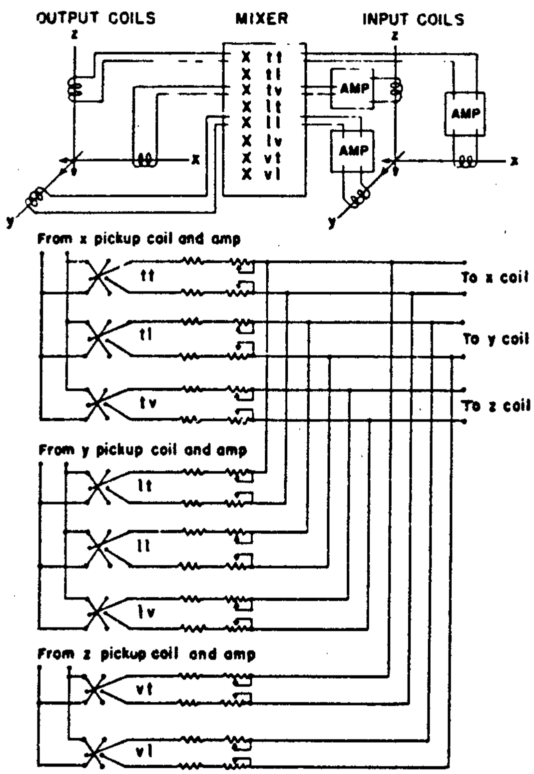


FIGURE 27. Schematic connections for most general case of eddy-current compensation.

fine the entire perm compensation procedure.

1. Pitch on east and west headings, adjusting L until $EP = -WP$.
2. Roll on north and south headings, adjusting T until $NR = -SR$.
3. Check the pitches on east and west heading for cross feed of T into L. It may be necessary to readjust L a small amount.
4. Check the north and south headings, trimming T to the desired value. Roll on east and west headings adjusting V for minimum noise.
5. The final check should be made by performing the tactical clover-leaf, right and left.

6.1.4 Compensation Equipment

Table 2 is a summary of the various methods of compensation discussed above. The pieces of electrical equipment mentioned will now be described.

TABLE 2. Summary of methods of compensation.

Type of field to be compensated	Active compensation	Passive compensation
Permanent	Adjustable perm compensator and variable field electromagnets. (Deperm all members possible.)	Proper placement of permanent magnets of the correct moment determined by calculation.
Induced	Electronic induced compensating amplifier, with connected magnetometers and output coils. (This unit used experimentally only.)	Strips of Permalloy positioned so as to cancel unwanted fields.
Eddy current	Electronic eddy-current amplifier, pickup, and output coils.	Copper rings or disks of the proper cross section, positioned properly to cancel out unwanted fields.

THE ADJUSTABLE PERM COMPENSATOR

The adjustable perm compensator consists of three electromagnets with steel cores of high

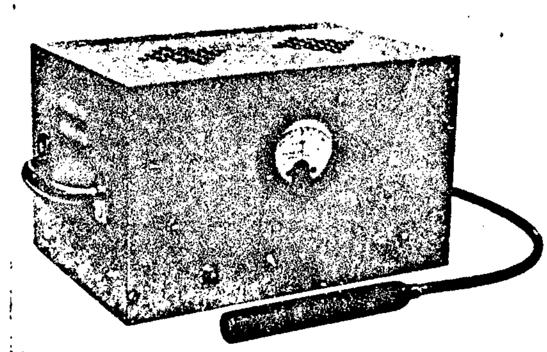


FIGURE 28. The a-c perm detector.

retentivity maintaining residual moments up to 4,000 cgs units. The electromagnets are mounted permanently in the airplane in such positions as to give three components at the

detector, one parallel to each of the three axes of the airplane, transverse, longitudinal, and vertical. There should be leads from the electromagnets to the junction box of the MAD installation with connections for the operation of the TS-7/ASQ unit. This unit (see circuit

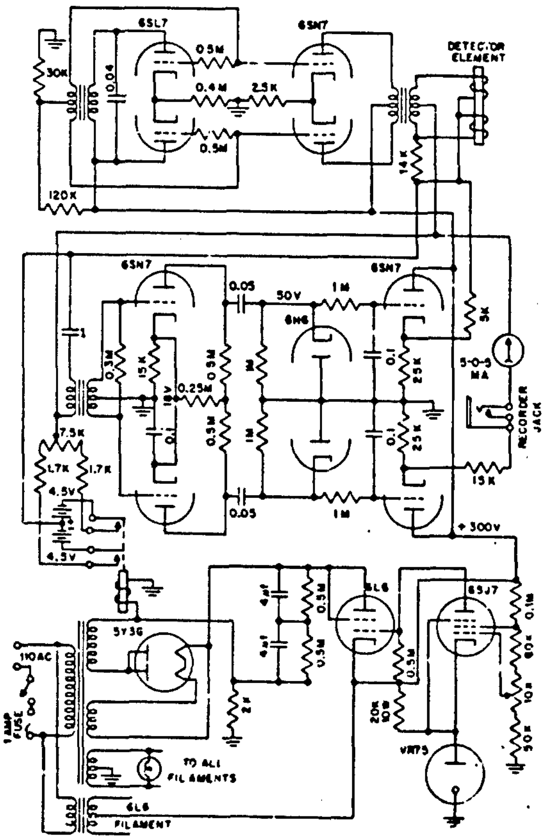


FIGURE 29. Schematic circuit of the a-c perm detector.

and photograph in Figures 19 and 20) operates on the 24-volt supply to the filament circuits of the MAD units and consists essentially of two potentiometers for coarse and fine control of the current in the electromagnets, and a current meter. A current-reversing switch makes it possible to reverse the polarity of the compensating magnets.

The actual adjustment of the moments during flight can follow a rather straightforward procedure. Since the signal is a direct indication of the needed compensating field, which in turn depends upon the moment of the magnet, a given disturbing field can be compensated by giving the electromagnets three or four values of current, and determining from a graph of current against signal the proper value of the current. It can be seen that this method of adjustment depends upon no previous knowledge either of the disturbing fields or of the polarity of the compensating fields, but only upon a few readily determined points on a current versus signal graph.

ELECTRONIC COMPENSATING SYSTEM FOR INDUCED FIELDS

In this system,[29] magnetometer detectors are installed rigidly in the plane with their axes parallel to the transverse and longitudinal plane axes. The signals resulting from the induced fields are amplified and combined as shown in Figure 21. The outputs are sent to

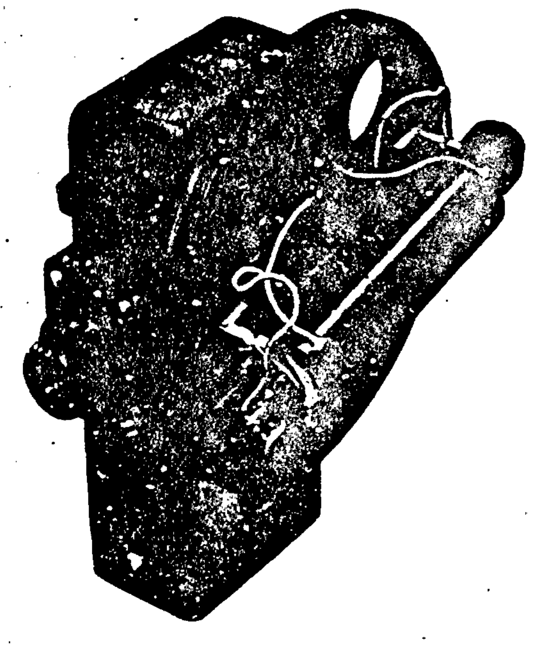


FIGURE 30. The d-c magnetometer element.

coils attached to the plane so as to produce current whose magnetic fields will oppose and cancel the undesired fields. The circuit diagram of one of the amplifiers is shown in Figure 22. Although this system did not receive extensive tests, it was found possible in some trials to

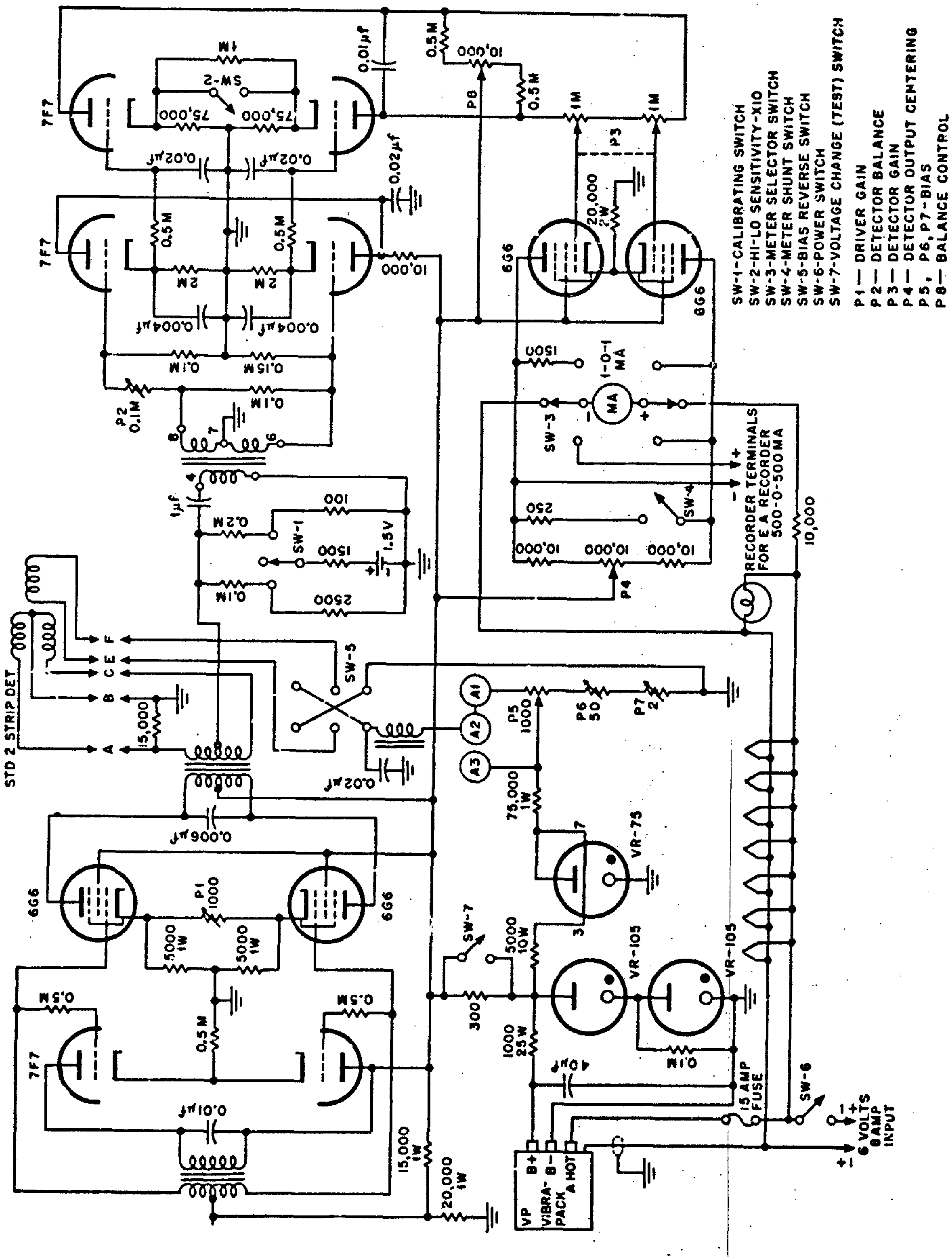


FIGURE 31. The d-c magnetometer circuit.

reduce the signals due to induced fields by a factor of 20 to 40.

EDDY-CURRENT COMPENSATOR[30, 32]

If a metal wing of an airplane moves through a magnetic field in such a manner that the total

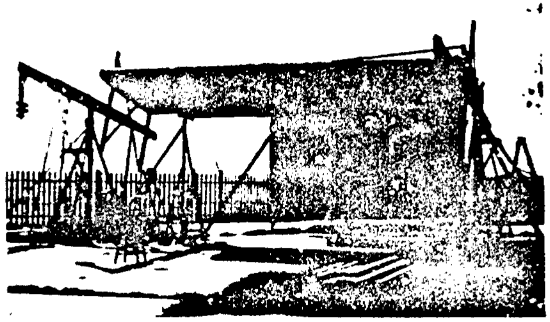


FIGURE 32. Experimental setup for measuring eddy-current effects from a PBY wing.

magnetic flux through the wing changes, then an electromotive force will be developed. This will cause eddy currents to flow in the wing and they will be proportional to the conductance of the metal. Also, the eddy-current loops will be

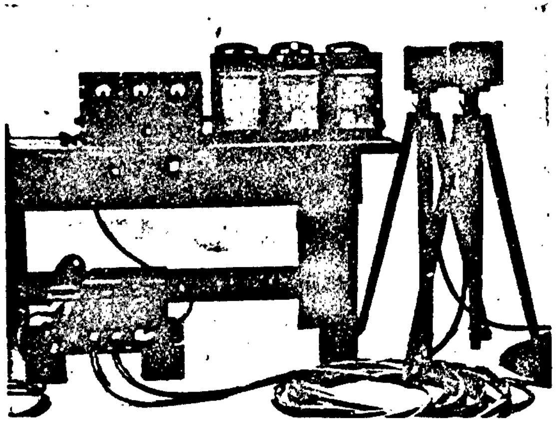


FIGURE 33. Setup for field measurements with the three-component gradiometer.

proportional to the wing area and will produce a magnetic field at right angles to it. To overcome this source of spurious indications the eddy-current amplifier, AM-36/ASQ, has been developed. It is shown in Figure 23.

The AM-36 unit is a three-stage band-pass amplifier employing degenerative feedback. The input to the amplifier is the voltage picked up by a coil with a large number of turns and of large cross-section area. This coil is placed in the airplane in such a position that the radial plane of the coil is parallel to the eddy-current loop. The AM-36 amplifies the input voltage and provides a means for reversing its phase. The output of the amplifier is connected to the compensating coil which is usually placed about 1.5 feet from the ASQ detector. When properly adjusted the current in this coil produces a magnetic field which is equal and of opposite phase to the field produced by the eddy currents at the detector. Figure 24 is a schematic circuit diagram.

The operating adjustments of this amplifier are readily made. The gain-controlling resistors, R19 and R20, are not installed at the time of manufacture but are selected by the person who

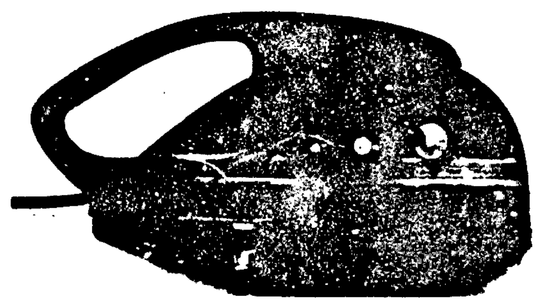


FIGURE 34. Inside view of induction magnetometer.

adjusts the unit. An L pad, shown in Figure 25, is inserted in place of the resistors by means of the jack connections, J1, on the panel. As the airplane is maneuvered to produce eddy currents, the gain of the AM-36 is adjusted by adjusting the L pad. When the correct gain has been determined the L pad is removed and the resistors, R19 and R20, corresponding to the two arms of the pad are inserted. Once these resistors are installed, the unit should require no further attention. Figure 26 shows a pickup coil installed in a TBF wing.

In the most general case three input coils, three output coils, three amplifiers, and a mixer would be required—connected as shown in Figure 27. However, it is evident that certain input and output coils are not required if the eddy-

current field is simpler than the general case. For leading-edge or wing-tip installations, it has been found that the only evident eddy-current components are $(rr - tt)$, tr, and rt. These three components may be obtained readily by using only one channel and tilting the input and output coils to obtain the cross terms.[33]

In addition to the above three devices for active compensation in flight, various other pieces

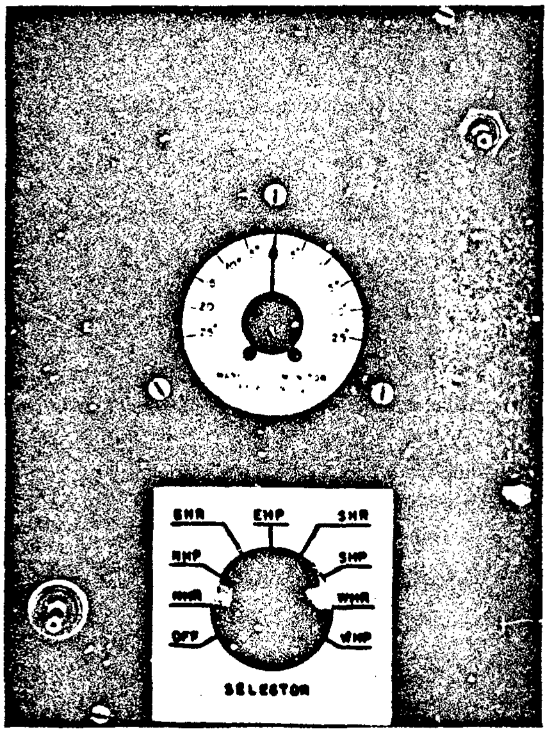


Figure 35. Pitch and roll indicator.

of auxiliary compensation test equipment were developed.

The A-C Perm Detector

This device, a low-sensitivity magnetometer, was designed to serve as a detector in the deperming of various struts and ferromagnetic members on aircraft. It is capable of measuring large fields without overloading, as it has negative feedback in the magnetometer element drive circuit. The magnetometer element is of the conventional two-strip type encased in a bakelized linen tube and connected to the detector-amplifier by means of a flexible cable (Figures 28 and 29). This instrument will measure fields up to $\pm 12{,}500$ gammas.

The D-C Magnetometer[34]

This test instrument was designed to fill the general requirements for the taking and recording of magnetic field strength measurements on the ground. Such measurements are required for landing gear struts, control cables, screws, rods, and other parts; the required instrument must be stable and sensitive over a range from less than 1 gamma to hundreds of gammas. This instrument became the basic measuring device for making magnetic field measurements for installations. It consists of a magnetometer connected to a d-c amplifier having a self-contained voltage-regulated power supply powered by a 6-volt storage battery. It uses a double-strip magnetometer element with either a self-contained microammeter, an Esterline-Angus recorder, or both as a means for reading and recording signals from magnetic fields. The detector element (Figure 30) is so mounted

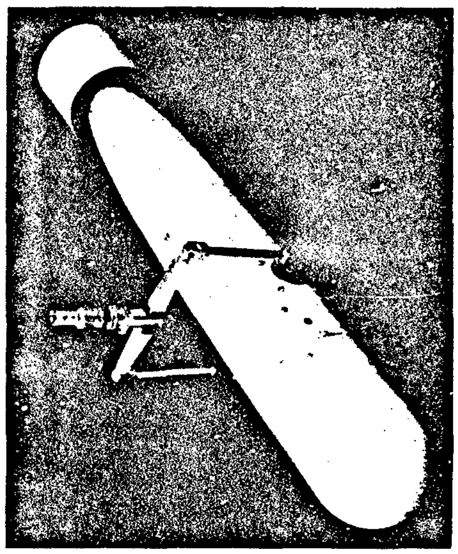


Figure 36. Towed bird with parallelogram bail.

that three field components, mutually perpendicular to each other, can be taken by moving the element about its two (vertical and horizontal) mounting axes. The rough bias for neu-

tralizing the effects of the earth's field is obtained by rotating a small magnet within the mounting block, while finer adjustments are obtained by varying the bias current within the amplifier. The circuit is shown in Figure 31.

A three-component unit was also made up, consisting of three conventional magnetometer elements mounted mutually perpendicular. Their outputs were connected to separate amplifier channels and recording meters, thus allowing measurements of three components of field strength to be taken simultaneously. Typical of the sort of special investigations which could be undertaken with these magnetometers is the *thick-wing study*. (Figure 32.)

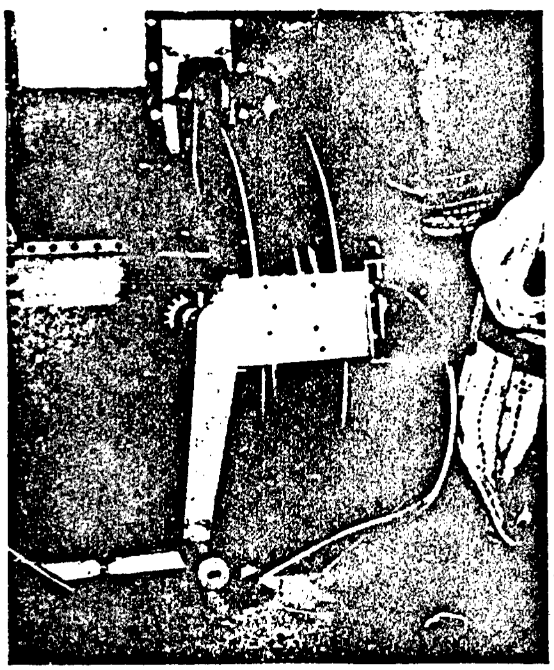


FIGURE 37. Winch for towed bird installation in TBF airplane.

The port outboard section of a PBY wing with trailing edge, retractable pontoon, and X-frame removed was mounted in a cradle. By means of a motor drive the wing could be moved to simulate pitches of the aircraft at a frequency of 0.2 c. The measurements were taken for a north heading of the aircraft. A d-c magnetometer was positioned at regular intervals along the center of rotation of the cradle, and field strength data taken for each position. Contour maps of the magnetic field strength were then plotted. The contours were found to agree with those calculated for a plain rectangular conducting sheet which is thicker at one edge than at the other. Additional data were taken with a flat aluminum sheet substituted for the wing.

THE THREE-COMPONENT GRADIOMETER

This instrument[c] was designed for the purpose of taking three-component magnetic field measurements simultaneously in the presence of noise from remote sources. The electronic circuit of its three channels is essentially that of the three-component d-c magnetometer. The main difference is in the design of the detector elements. The two strips of the magnetometer element are separated by a distance of 50 feet or more and are connected as a gradiometer. In practice, one detector (the signal detector) is placed near to the field under measurement. The other (the reference detector) is placed at some distance, and the noise that affects both detectors alike will cancel. This instrument is most useful when magnetic field data are required in locations where excessive magnetic disturbances from sources such as electric railroad lines are present. The entire unit, including power supply, heads, and recorders, is shown in Figure 33.

LOW SENSITIVITY INDUCTION MAGNETOMETER

This instrument[36] was designed for use as a magnetic detector requiring no external connections other than a 3-volt dry battery. It consists of a standard d-c 1-0-1 milliammeter with its field magnet removed and replaced by a Permalloy dipole antenna. (Figure 34.) The dry battery is connected to the terminals of the moving coil which provides a fixed field. A current of approximately 80 ma passing through this winding produces a sensitivity of about ± 15,000 gammas full scale. In operation, the earth's field is balanced out by means of a small rotatable magnet within the case, and the sensitivity may be adjusted by changing the constant field. This instrument also has possi-

[c] Another gradiometer, devised by the Naval Ordnance Laboratory, is described in reference 35.

bilities for use as a pitch and roll indicator and as an induction-type d-c ammeter.

PITCH AND ROLL INDICATOR

This instrument was designed for use during compensation flights to facilitate the correlation of maneuver noise with the pitching and rolling maneuvers of the airplane. The indicator used in conjunction with this instrument can be either a microammeter (Figure 35) or an Esterline-Angus tape recorder, the latter being useful when an analysis on the ground of maneuver noise and motions of the aircraft is necessary.

This device is essentially a low-sensitivity magnetometer incorporating d-c negative feedback as a means of stabilizing the detector element to keep it from overloading. The detector consists of two double-strip elements placed mutually perpendicular in a horizontal plane and so placed in the aircraft as to give indications of the angular motions of the airplane with respect to the vector of the earth's field as the plane flies on cardinal headings. The switch on the front panel is marked to denote pitches and rolls on the cardinal headings.

COMPENSATION TRAINER

A trainer was designed for the purpose of instructing personnel in compensation techniques. This device made possible the simulation of actual ferromagnetic and eddy-current fields in all types of Service aircraft. A problem could be set up by the instructor, solved by the student, and the results noted. The device was used jointly by the research staff and the training department of AIL for working out compensation problems.

The next sections take up the other method of eliminating the effects of magnetic noise from the aircraft.

6.2 THE TOWED BIRD[d]

It is probable that if a noise level of less than 2 gammas is needed during violent maneuver of the airplane, the head should be towed behind the plane in the manner shown in Figure 8 of Chapter 1. And in general it is considered that the low noise level during straight and level flight with this system might increase the range of detection in service by as much as a factor of 1.5 compared to the compensated internal installations.

In early experiments,[40] the streamline housing or bird was designed to accommodate a

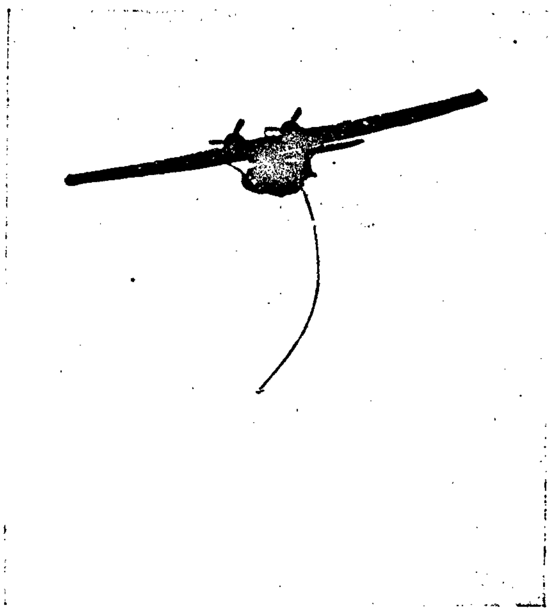


FIGURE 38. Behavior of towed bird during a roll.

head-motor assembly of the general type used in MAD Mark IV equipment and was formed of an air-drying plastic material laminated with jute cloth. A tail structure comprising a cylindrical fin of approximately the same diameter as the bird and spaced therefrom by four struts was provided to improve the aerodynamic stability of the unit. This bird was suspended on a cable having 14 conductors and a phosphor bronze strain core. This cable was accommodated in the aircraft on a target-towing winch, and arrangements were made for flying the bird at various cable lengths.

Two methods of attachment of the cable to the bird were investigated. In one of these the cable was connected directly to a fitting on the top of the plastic shell above the longitudinal center of gravity of the bird, while in the other

[d] Some towed bird experiments were also carried out by the Naval Ordnance Laboratory.[37-39]

a bail structure was utilized which supported the bird at the center of gravity and permitted relative motion between the bird and the cable with 2 degrees of freedom. Initial experiments comparing these two types of attachment did not show any significant difference as far as performance was concerned, although with both it was found that the bird had much less stability than the towing aircraft and that the servo system of the detection equipment was not capable of following relatively fast motions of the bird transmitted thereto by the cable. In addition, it was found that when relatively short cable lengths were used variations in the separation between the aircraft and the bird during maneuvers or rough air caused noise. Such noise was presumably due to changes in the effect of the magnetic field of the aircraft on the detection equipment and was eliminated in later experiments through the use of cable lengths of approximately 200 feet.

In an effort to improve towed bird performance, various means were investigated for damping the motion of a bail-suspended bird. In one of the damping systems rubber was used to provide a restoring force, while in another a hydraulic damper in which oil was carried from one chamber to another through an adjustable orifice was used. A third type of damper involved the use of mercury in a coiled tube which was mounted inside the bird.

At about the same time, a flight test was made to determine the feasibility of mounting the bird on a 12-foot strut which could be lowered while the aircraft was in flight to provide a rigid support for the bird beneath the aircraft. While no difficulty was encountered in raising or lowering the strut, persistent vibrations at amplitudes and frequencies such that detector operation was impractical were encountered. This, plus the fact that support problems would obviously become more difficult as the strut was extended to practical lengths, caused abandonment of this approach in favor of the cable method of suspension.

The development of the type AN/ASQ-1 equipment with the relatively small DT-1/ASQ-1 head and a more efficient servo system added impetus to the towed bird investigation.[41, 42] A streamline wooden housing of the type used for wing-tip installations was fitted with a tail structure of aluminum and an improved bail for attachment to the towing cable. This equipment is shown in Figure 36. The aluminum tail structure, which was later replaced by one of plastic, was cylindrical in form and had a diameter which was the same as the largest diameter of the bird. This structure was supported by four longitudinal fins, two of which were vertical and two of which were horizontal. The bail structure was designed to isolate the bird from forces which would otherwise be transmitted to it by the connecting cable. This so-called parallelogram bail provided 2 degrees of freedom permitting the bird to pitch and roll.

The bail structure included two nonmagnetic ball bearings which were mounted in Dural plates on either side of the housing at the longitudinal center of gravity, which was artificially located approximately one-third of the distance from the nose to the tail by means of segmental lead weights mounted inside the housing. Two short rods extending from the bearings to the outside of the housing provided a support axis normal to the longitudinal axis of the bird. Hollow arms, each equal in length to the diameter of the housing, were pivoted at the outer ends of the rods, and the upper ends of these arms pivotally connected to a third hollow arm which completed the parallelogram. The several hollow arms and rods accommodated the electrical connections from the towing cable to the head-motor assembly. This structure permitted motion of the bird in respect to the cable with 2 degrees of freedom. Initially, the towing cable was connected to the bail by a standard Amphenol AN-type connector, rigidly connected to the upper bar of the parallelogram. This arrangement was soon replaced with the one shown in the illustration, in which the plug was pivoted to allow motion of the cable in respect to the upper bail arm about an axis parallel to the longitudinal axis of the bird, thereby preventing oscillations of the cable from exerting any forces tending to cause the bird to roll.

Initial experiments were carried out using a cable having 14 conductors and a phosphor bronze strain cable; this was replaced for later experiments by a special cable having no strain

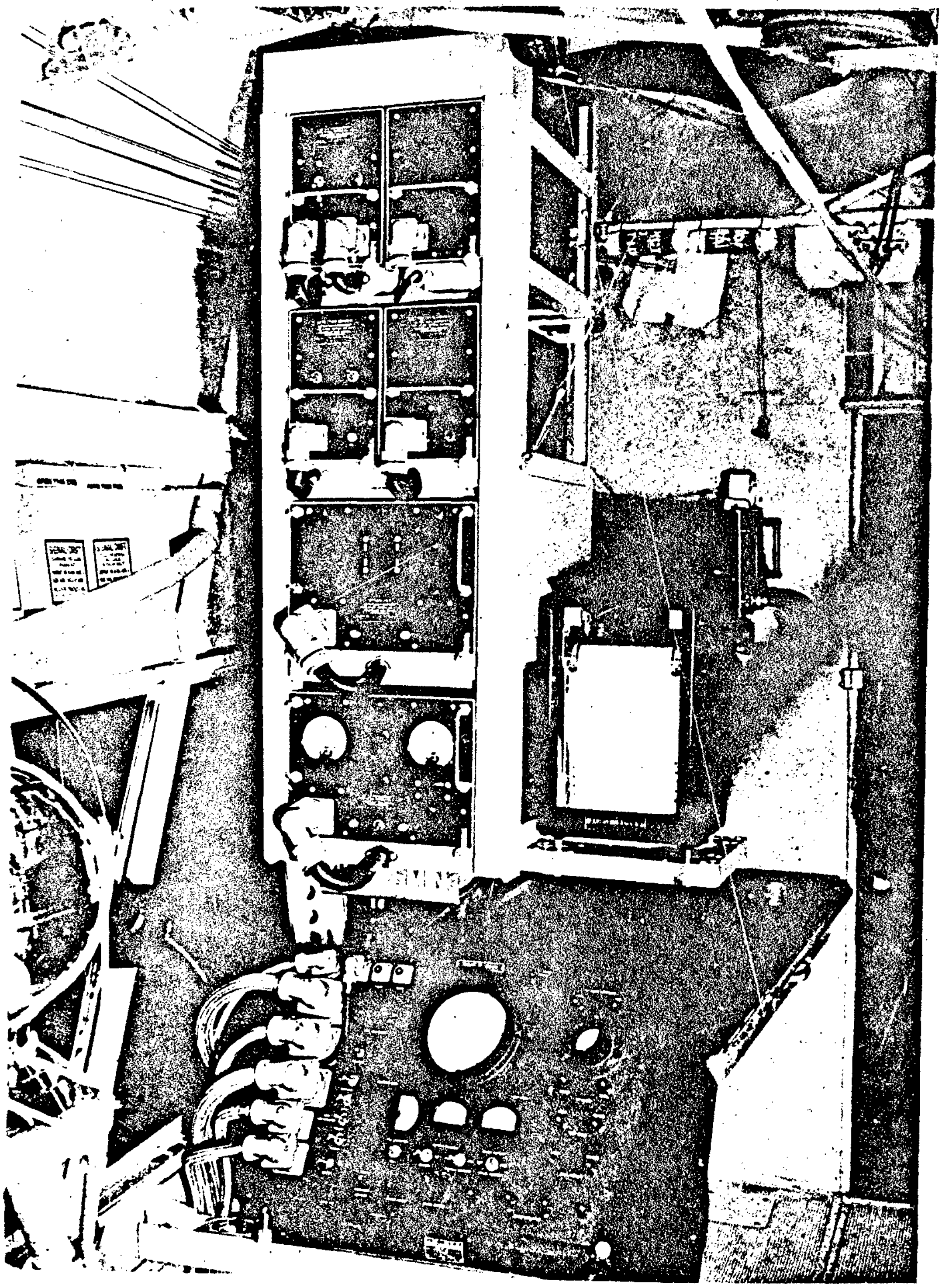


FIGURE 39. Mark IV B-2 MAD rack installation in K-type blimp.

cable and 12 solid conductors. This cable was accommodated on a target-sleeve towing reel (Figure 37) with the connections at the inner end of the cable brought out to a connector mounted on the reel. This equipment, together with the remaining units of an AN/ASQ equipment, was mounted in a type PBY-5A airplane for testing, the reel being so positioned that the bird could be flown from the tunnel hatch. After the bird had been lowered to the desired cable length, the reel was locked, and electrical connections were made between the AN/ASQ-1 equipment and the connector mounted on the reel.

A large number of test flights were made at Quonset Point, and simultaneous records were taken with bird-mounted and tail-cone-mounted equipments. In a comparison of these simultaneous records, it was found that a somewhat lower average noise level for straight and level flight could be obtained with the towed bird than with the equipment mounted directly in the aircraft. During maneuvers, the bird followed the aircraft well if the maneuver was executed smoothly. (For example, see Figure 38.) However, during very sudden maneuvers the system was less stable.

6.3 MAD SERVICE INSTALLATIONS

Between July of 1941 and July of 1944, over 400 installations of MAD equipment were made. While many of these installations were actually made by the Services, most of them were designed or supervised by Laboratory personnel.

Lighter-than-Air Installations

While the early MAD experiments were made in Navy PBY airplanes, the first Service installations were made in the blimps at the Lakehurst Naval Air Station. The success of these early installations was such that MAD became standard equipment for all blimps in antisubmarine service. Figure 39 shows the standard Mark IV B-2 rack installation in the forward portion of the control car. Over 100 of these installations were made in K-type airships.

In the fall of 1943, an experimental installation of AN/ASQ-2C equipment was made on a K-type airship. More of these installations were made in the spring of 1944, and by the middle of 1945 more than 60 K-type airships had been so equipped.

As it is possible to locate the magnetometer head at a considerable distance from the steel structure of the control car and engines, and as the maneuvers of an airship are considerably less violent than those of an airplane, it usually has not been found necessary to compensate LTA installations.

Heavier-than-Air Installations—Mark IV B-2

The early experimental tests were made with the magnetometer head mounted in the hull of a PBY-1 patrol bomber. While this type of installation was useful for experimental work, it was unsatisfactory for Service use as the head was too near personnel and material in the airplane. Later installations were made with the head mounted in the extreme rear of the hull. Where the dip angle is about 70° little trouble is encountered in satisfactorily compensating the permanent fields of the airplane. Tests made at San Diego and Key West indicated, however, that for lower dip angles such compensation would be difficult.

In the spring of 1942, the Army initiated an extensive program of MAD installations in B-18 airplanes in a tail cone. The appearance of this was such that it was quickly and aptly called a "stinger." Under the general supervision of AIL, a total of approximately 100 installations of this type were made. During August of 1942, an experimental installation was made in the tail of a B-25 medium bomber. Because of the presence of a large amount of steel fittings, the installation was unsatisfactory. In September of 1942, an experimental installation was started on an Army B-34 bomber. A special Mark IV B-2 head was designed in order to make possible the use of a smaller tail cone, but no Service use was made of MAD in this airplane. Following the success of the B-18 tail-cone installation, a similar mounting was designed for use of PBY's. This proved very successful and placed the equipment in a position relatively free from disturbing magnetic fields, which made for easy and reliable com-

pensation. Several experimental installations of this type were made at Quonset, and an entire squadron (VP-63) was so equipped at San Diego.

Heavier-than-Air Installations—AN/ASQ-1, 1A, 2, 2A

With the development of the lightweight, compact AN/ASQ-1 equipment, dual installations in large airplanes became practical and single installations in small airplanes economical from the weight standpoint.

Fifty-seven of these installations had been made by July 1944.

Field Engineering

Because of the speed with which MAD equipment went into Service use and because it represented a new type of equipment for which there was little background of experience, AIL had to furnish a considerable amount of field engineering assistance. Laboratory engineers were sent to many of the lighter-than-air bases and with most of the MAD-equipped squadrons.[43-45] These engineers aided in the installation and maintenance of equipment, helped train Service personnel, and brought back to the laboratory information needed for the design of new equipment.

Chapter 7

TRAINING DEVICES AND EXPERIMENTAL EQUIPMENT

7.1 MAGNETIC ATTACK TRAINER

7.1.1 General Description

THE TYPE 3 *magnetic attack trainer* [MAT-3][1,2] is intended for use in training blimp personnel in the tactical use of AN/ASQ and sono buoy equipment. It provides means for simulating at a reduced scale the tactical conditions occurring in the use of the equipment, thereby permitting personnel to be trained without necessitating withdrawal from service of actual material.

The MAT-3 is an improved model of the original magnetic attack trainer,[3] which was built and permanently installed at the Airborne Instruments Laboratory during the winter and spring of 1943 and was used in the training of both lighter- and heavier-than-air personnel of the U. S. Navy. The improved trainer was constructed for the lighter-than-air branch and was particularly designed for such use.

It was required that the trainer be a complete unit in and of itself which could, if necessary, be moved from place to place. Certain improvements leading to more realistic simulation of the tactical problem were also requested.

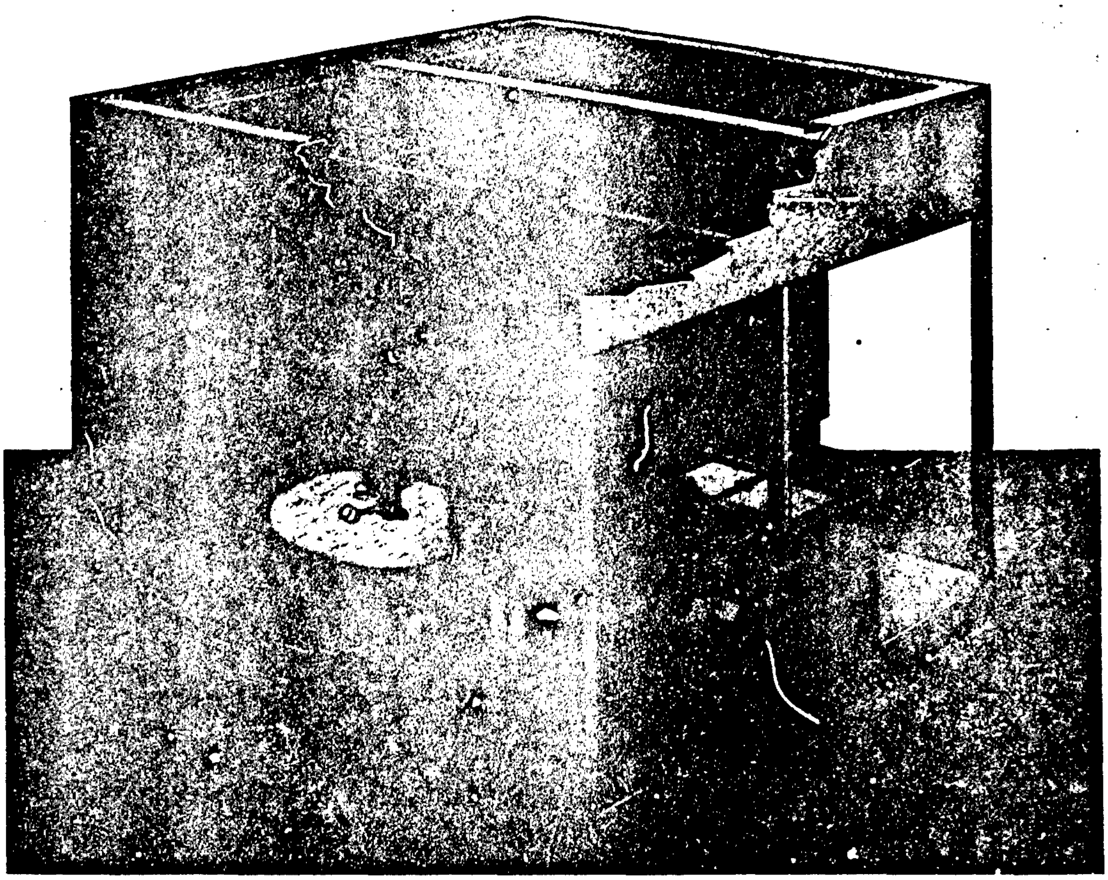


FIGURE 1. Perspective drawing of MAT-3.

The MAT-3, shown in Figure 1, includes a

scale model tactics area in which a model submarine and a model blimp may be maneuvered independently in response to separate sets of remote controls. The submarine model is provided with means for generating a magnetic field scaled to that of an actual submarine and varying properly with changes in heading. Suitable adjustments are provided so that submarines having various types of magnetization may be simulated for any desired magnetic dip angle.

The blimp model is provided with simulated AN/ASQ equipment which is arranged to detect the magnetic field of the submarine model and to produce output indications simulating with a high degree of verisimilitude those obtained with the AN/ASQ equipment under corresponding conditions. The speeds of the two models and the vertical distance between them (representing the altitude of the blimp plus the depth of the submarine) may be varied to demonstrate the effects of these factors on the operation of the AN/ASQ equipment. The effects of wind on the operation of a blimp may also be simulated. The MAT-3 is arranged to simulate either the AN/ASQ-1 or AN/ASQ-2B installations as desired.

Since in actual practice the blimp pilot cannot see the submarine, the tactics area in the MAT-3 is so positioned as to be out of sight of the pilot-trainee. Such information as to the position of the blimp and its course as may be available to the pilot of an actual blimp during a tactical period is made available to the pilot-trainee in the MAT-3 by means of an indicating system. This system includes a scale model of the tactics area which is mechanically linked to the blimp model drive and moved beneath a fixed observation point in accordance with the movements of the model blimp in the tactics area. The observation point, which represents the blimp, is located close to the surface of the scale model in order to maintain realism. Accordingly, an optical system is provided by means of which the pilot-trainee is effectively positioned at the observation point.

The float lights or flares used in conjunction with the AN/ASQ equipment are reproduced and appear on the scale model ocean of the pilot's indicating system. Also provided are means for simulating the dropping of bombs from the blimp and for recording the results of bombing attacks.

A second indicating system operates a recording table on which the paths of both the submarine and blimp models during a training exercise are permanently recorded for reference purposes. The locations of the two models at the instant when bombs or flares are dropped are also recorded. This indicating system forms part of the equipment provided for the use of an instructor. The instructor is also furnished with duplicates of the blimp controls and with controls for the submarine model.

Certain of the control and indicating equipment of the MAT-3 is provided in duplicate so that an aviation radioman (ARM) and a pilot may be trained simultaneously, each performing the duties which he will perform in actual practice.

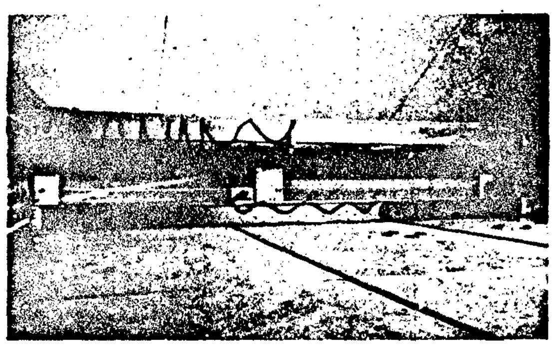


FIGURE 2. Tactics area, MAT-3.

The sono buoy training equipment includes means for simulating submarine sounds and background noises as heard from buoys dropped at a number of positions in the tactics area. The signals from the listening positions may be monitored selectively at the pilot's and ARM's positions using headphones. An intercommunication system connecting the instructor's, pilot's and ARM's positions also utilizes the headphones and the amplifiers associated therewith.

The MAT-3 equipment is mounted on a structural steel framework 10 feet 4 inches by 12 feet by 9 feet 6 inches high, which is supported at the four lower corners. This structure consists of two decks, the upper of which is occupied by a tactics area 8 by 10 feet reproducing,

at a scale of 300 feet to 1 inch, an area approximately 4.8 nautical miles north and south by 6 nautical miles east and west. The submarine and blimp models and their associated translating mechanisms are accommodated on this deck and are shown in Figure 2. The lower deck is laid out as shown in Figure 3 and accommodates the electronic equipment mounted in relay racks; the pilot's, instructor's, and ARM's control positions; the pilot's indicating system; and the recorder table.

The control and drive systems and the electronic equipment of the entire trainer are shown in operating relationship in Figure 4, pictorial schematic of MAT-3.

7.1.2 Blimp and Submarine Translation Systems

The blimp and submarine models are mounted for movement in the tactics area on suspensions similar to those used in bridge-type cranes. The submarine model is mounted on a carriage arranged for movement back and forth along a beam which is itself arranged for movement over the tactics area. The beam provides for movements of the model in the east and west direction while the carriage provides for travel in the north and south direction.

The suspension for the blimp model is similar in all respects to that of the submarine

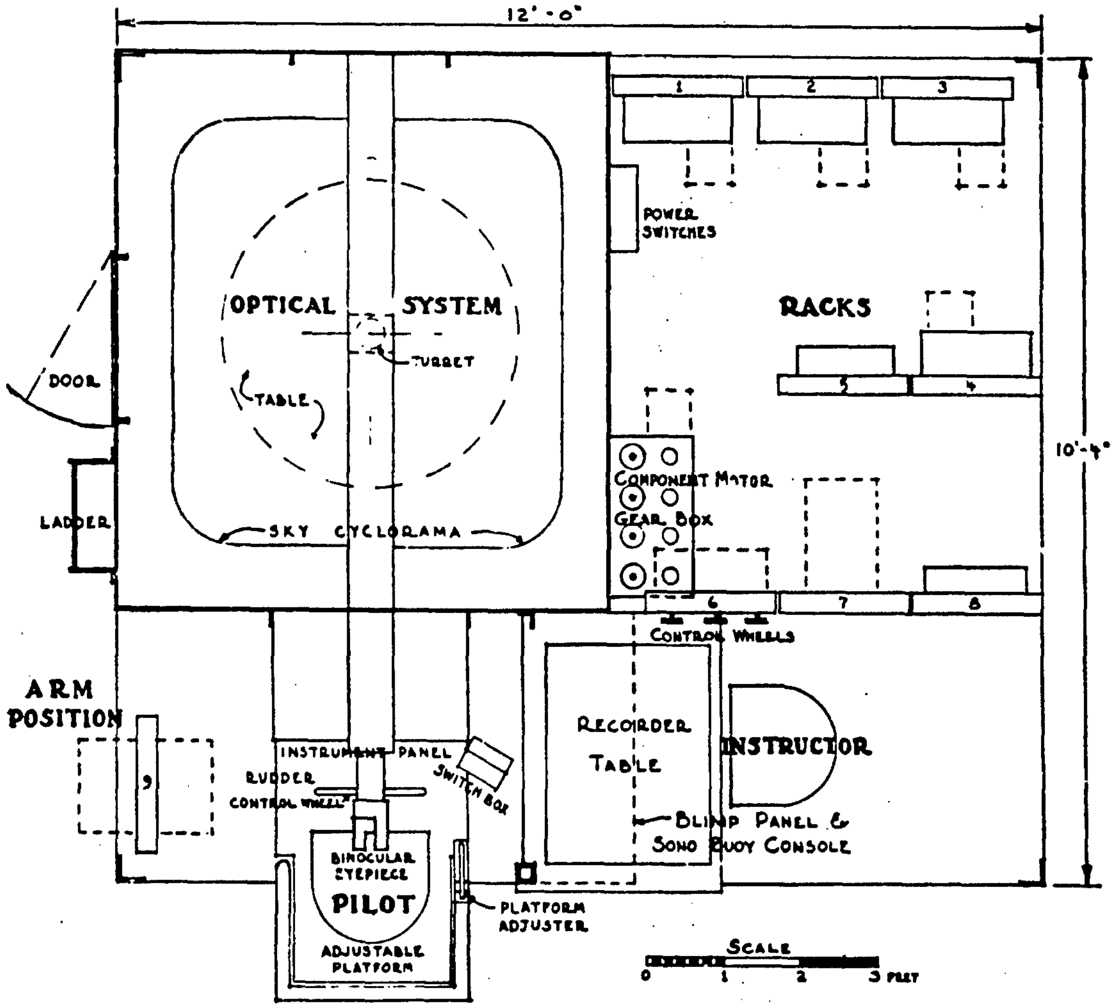


FIGURE 3. Layout of lower deck, MAT-3.

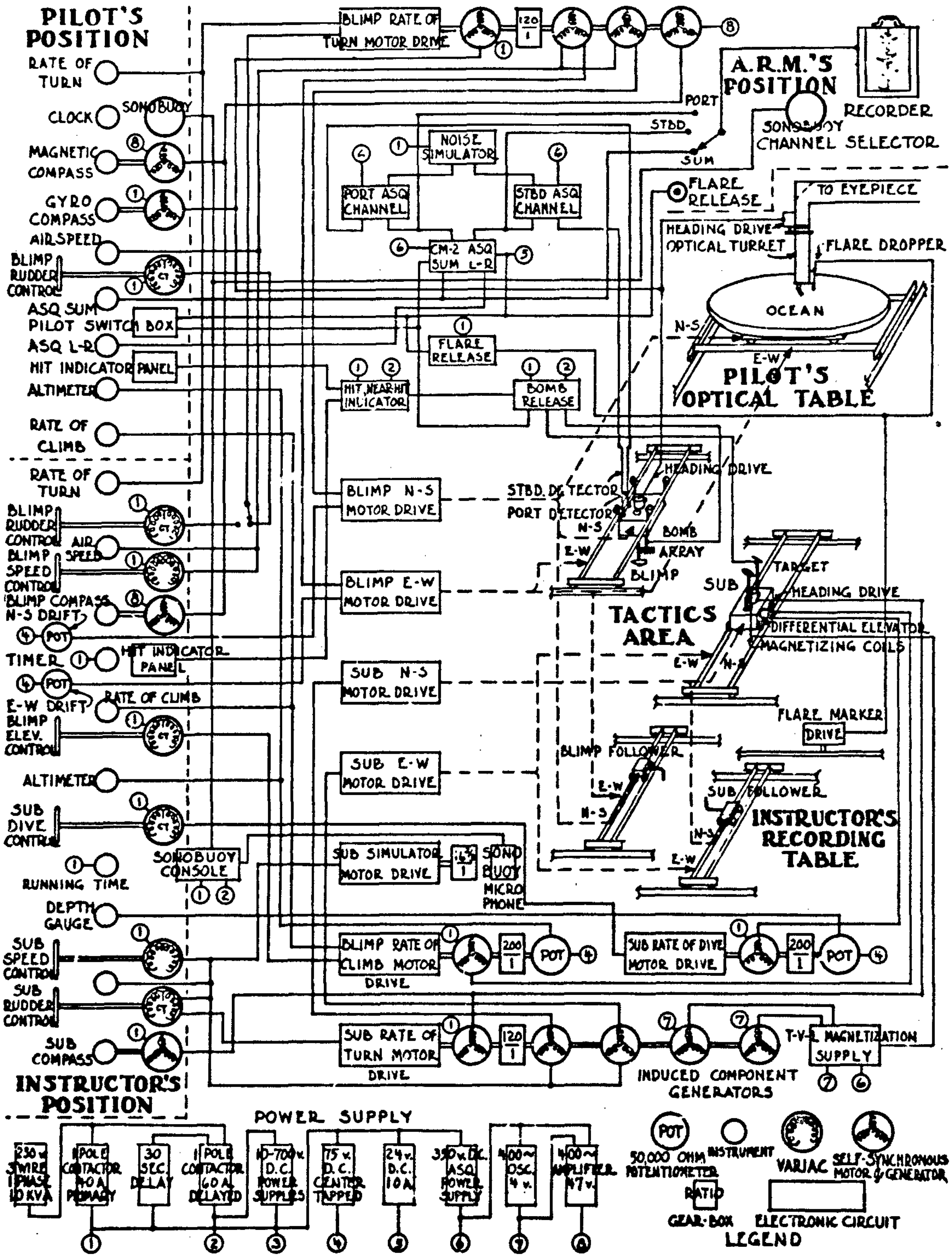


FIGURE 4. Pictorial schematic of MAT-3.

model and is mounted immediately above the latter in such fashion that the two models may move independently to all positions in the tactics area without interference. Motion is transmitted to the respective beams and carriages of the blimp and submarine translation systems by means of four cable systems which pass around four drive drums located on the lower deck of the MAT-3. These four cable systems are independent and those for the two beam movements are so arranged that the beams are restrained from yawing and binding in their guides as they move over the tactics area.

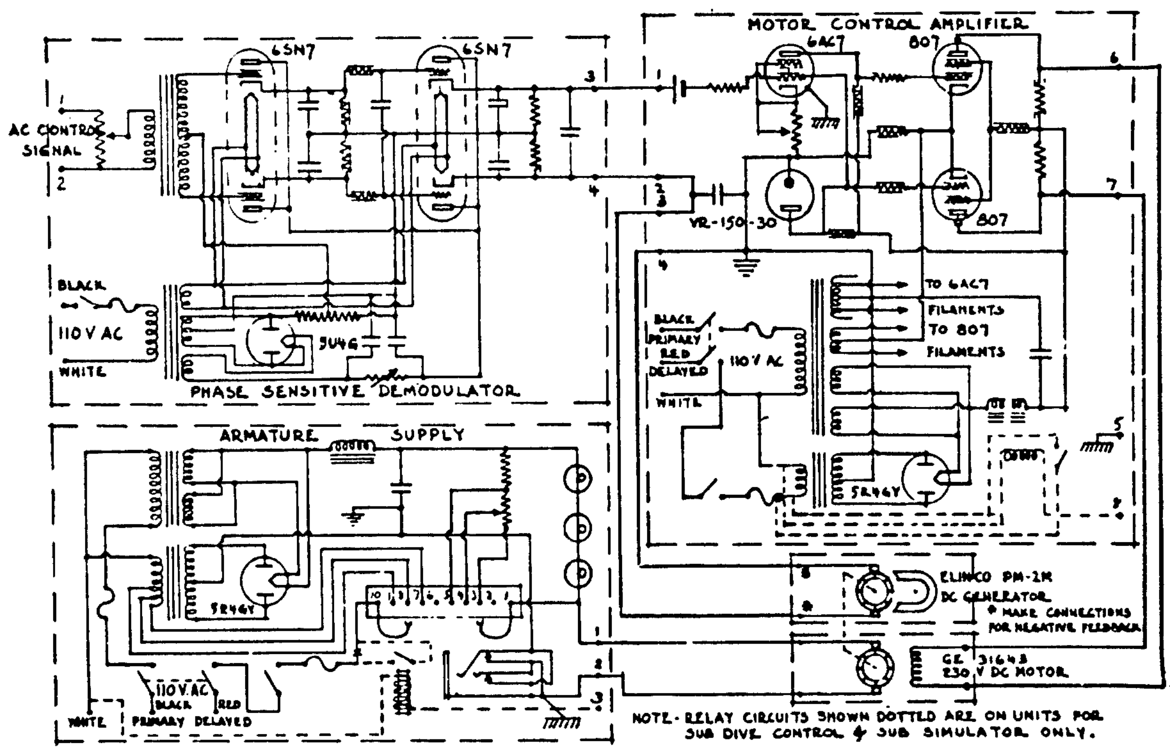


FIGURE 5. Motor control circuit of MAT-3.

Each of the four cable-system drive drums is rotated by means of a d-c motor. Since the steering controls of a blimp or submarine establish a rate of turn, it is necessary that mechanism be provided to obtain, from the rate of turn so established, information in accordance with which the rectilinear velocities of the beam and the carriage of the associated translation system may be appropriately adjusted to establish the required rate of turn. This is accomplished by means of rotatable transformers, the shafts of which are driven through reduction gearing by a motor controlled by the rate-of-turn control. One of these rotatable transformers is arranged to produce a voltage varying with the sine of the angle through which its shaft is rotated, while the other is arranged to produce a voltage proportional to the cosine of the same angle. Since the motor speed is proportional to the desired rate of turn, the shaft rotation of the rotatable transformer may be made a direct measure of the heading angle. The control signal obtained from each of these rotatable transformers is thus an a-c voltage, the amplitude of which varies in accordance with the sine or cosine, respectively, of the heading angle and the phase of which reverses at zero. A special motor control system is provided to operate the d-c translation-system drive motors in response

to a-c control signals, this system being designed also to provide substantially constant torque at all motor speeds between zero and a maximum speed and to produce a motor speed which is a linear function of the control voltage unless the motor is actually stalled.

The motor control systems[4] each comprise four units in addition to the controlled d-c motor. These units are a phase-sensitive demodulator, a "constant"-current power supply, a motor control amplifier, and a permanent-magnet generator. Briefly, the a-c control signal is demodulated to obtain a d-c voltage which varies in amplitude and polarity with the amplitude and phase of the control signal. This d-c signal is used to control a d-c motor with separately excited armature and field windings, the armature being supplied from a substantially constant current source. The d-c control signal is power amplified and supplies the field current, variations in which cause corresponding variations in the speed and direction of rotation of the motor. The permanent-magnet generator is coupled directly to the shaft of the motor and supplies a feedback voltage to the motor control amplifier such that variations in speed of the motor due to changing loads are overcome. A complete motor control system of this type is shown in Figure 5.

In the operation of a typical motor control system embodying these units, the application of an a-c control signal to the input of the phase-sensitive demodulator causes the production of a d-c potential at the input of the motor control amplifier. This results in a large increase in the field current of the motor which, assuming that the armature is excited with "constant" current, causes the motor to start, the direction of rotation depending on the phase of the a-c motor control signal. The motor drives the permanent-magnet generator, the output of which is very nearly linear with speed. The polarity of the generator output voltage is such as to oppose the signal at the input of the motor control amplifier. This causes a decrease in the motor speed, which in turn reduces the voltage fed back to the control amplifier from the generator. Accordingly, the system reaches an equilibrium speed for a given signal voltage. The motor control amplifier, being responsive only to the difference in voltage between the control and feedback signals, causes large changes in field current whenever the motor speed changes by a few rpm whether the motor is operating at high or low speeds. Thus the motor delivers torque even at very low speeds since any force tending to reduce the shaft speed causes a large increase in field voltage tending to accelerate the motor until the equilibrium speed determined by the signal voltage is re-established.

This motor control system is used for all motor drives in the MAT-3. In a typical installation shown in Figure 6, two armature

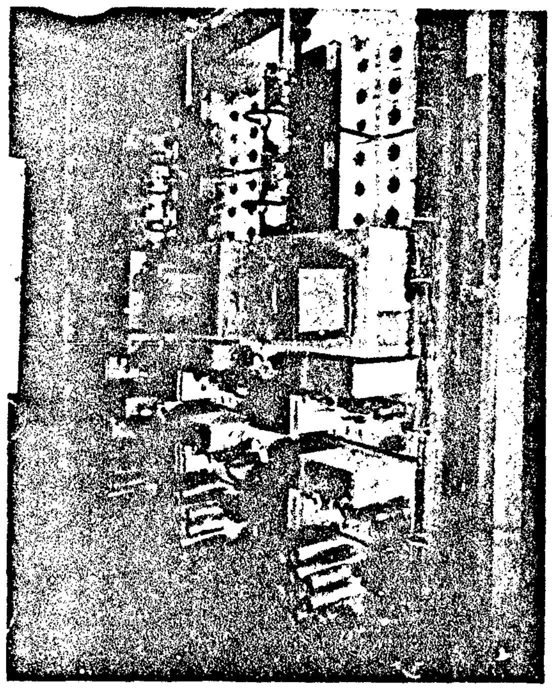


FIGURE 6. Motor control system racks, MAT.

power supply units, a chassis housing two phase-sensitive demodulators, and two motor control amplifiers are mounted in a single relay rack, together with a single motor drive unit. A single rack thus accommodates a complete motor control system plus all the units of a second system with the exception of the motor and the generator.

As mentioned above, each of the four cable systems of the blimp and submarine drive sys-

tems is driven by means of a d-c motor controlled by one of the motor control systems just described. In the blimp translation drive systems provision is made to permit overrunning of the drive after the beam and carriage have reached the limits of their travel. However, this drive system permits the pilot-trainee to perform maneuvers beyond the limits of the tactics area, motion of the blimp model in the area always starting at the angle and position determined by the maneuver performed in the overrun area.

STEERING CONTROL SYSTEMS

The submarine steering control system is operated from the instructor's position as shown schematically in the pictorial schematic of the MAT-3, Figure 4. The control wheel, which establishes a rate of turn, turns a center-tapped variable autotransformer providing an a-c control signal, the phase of which varies with the direction of turn and the amplitude of which is dependent upon the rate of turn. This control signal is used to control a d-c motor through a motor control system of the type described above. The speed of the submarine along its path is determined by the voltage applied to the single phase windings of the rotatable transformers, this voltage being controlled by means of an autotransformer operated by a control wheel at the instructor's control position. Since the turning radius of a submarine remains substantially constant for all speeds, it is necessary to increase the speed of the submarine rate-of-turn motor drive as the submarine speed is increased. This is accomplished by applying a portion of the output voltage of the submarine speed control autotransformer to the submarine steering control autotransformer.

The blimp steering control system is similar to the submarine steering control system and, as shown in the pictorial schematic, Figure 4, may be operated from either the pilot's or the instructor's positions. A switch is provided at the instructor's position for shifting the control from a center-tapped variable autotransformer at that position to an identical autotransformer at the pilot's position. In either case the autotransformer provides an a-c control signal which determines the operation of the motor control system. The speed of the blimp along its path is controlled by varying the voltage applied through a variable autotransformer to the single phase windings of the rotatable transformers mentioned above. Provision is made for simulating the effects on the course of the blimp due to winds having various velocities. Such winds are simulated by applying additional control voltages to one or both of the blimp translation system motor drive units. The proper voltages for this purpose are obtained by means of two potentiometers, one for north-south wind components and one for east-west wind components, located at the instructor's control position and connected to the output of a regulated 75-volt d-c power supply. These potentiometers provide a range of wind velocity adjustment for each cardinal direction extending from 0 to 40 knots. Winds from intercardinal directions are simulated through the use of both control voltages.

For convenience, all adjustments in the vertical separation between the blimp and submarine are effected by means of an elevator associated with the submarine model. A differential control system responsive to blimp altitude and submarine depth controls is provided to govern the operation of the elevator. The blimp altitude control system includes a center-tapped variable autotransformer by means of which an a-c signal of proper phase and amplitude is applied to the input of a motor control system. The submarine dive-control wheel actuates a second motor drive system which drives a second selsyn generator through a gear box. At the upper limit of the range the stop mechanism operates a "surface" switch which doubles the speed of the submarine model. The rotation of the differential selsyn on the submarine model is proportional to the algebraic sum of the rotations of the two selsyn generators included respectively in the blimp and submarine altitude and dive control mechanisms. Accordingly, the total separation between the two models is appropriately varied by the single elevator on the submarine model whether changes in the separation between the two are due to changes in the altitude of the blimp, changes in the depth of the submarine, or both.

7.1.3 Blimp, Submarine, and Detector Models

The submarine model shown in Figure 7 is mounted on the carriage of the submarine translation system. The dimensions of this model are scaled to those of a typical submarine at a scale of 300 feet to 1 inch and means are provided for simulating the magnetic field of the prototype. The model is mounted on a vertical shaft rotatably supported on the submarine carriage and driven by the submarine heading selsyn receiver through a train of spur gears. A circular rack is cut in the shaft and a second train of gears driven by the elevator differential selsyn receiver is arranged to raise and lower the shaft in respect to the carriage. The required connections to the three magnetic field generating coils on the submarine model are made through slip rings mounted on the shaft. Also mounted on the submarine model carriage is a target model which forms a part of the simulated bombing system.

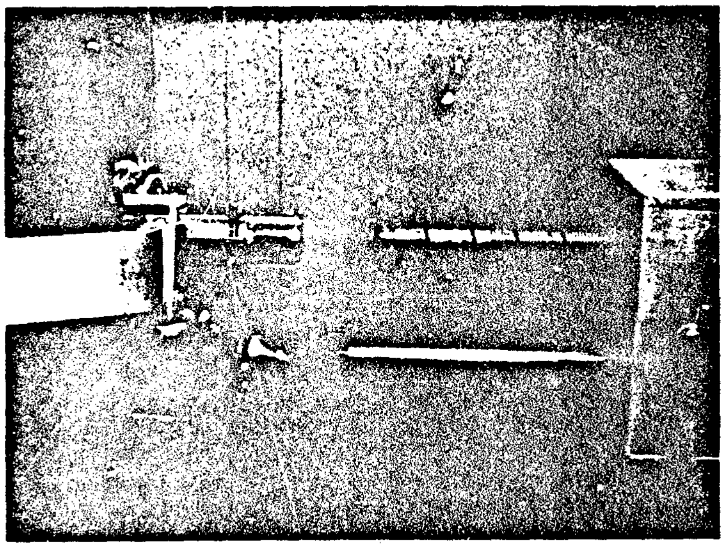


FIGURE 7. Blimp and submarine models.

The magnetic field of a submarine is simulated in the MAT-3 by means of an a-c field, the amplitude of which is made to vary in accordance with the amplitude variations of the d-c field of an actual submarine and the phase of which is determined by the polarity of the field of the submarine to be simulated. The system is equivalent to that used in the model signal studies described in Chapter 4.

The blimp model is mounted on the carriage of the blimp translation system and includes a pair of pickup coils mounted to simulate the port and starboard detectors of an AN/ASQ-2B installation. Provision is made also for simulating the operation of the ASQ orientation systems. The pickup coils are mounted for rotation about horizontal axes supported by a pair of vertical shafts. These shafts are rotatably mounted on a column extending vertically from the blimp carriage and itself mounted for rotation in respect to the carriage. Back gearing and flexible linkage between the column drive and the two pickup coil shafts maintain a constant space orientation of the horizontal coil-supporting axes irrespective of rotations of the vertical column. The two pickup coils are thus maintained in parallel vertical planes at all times, and their orientations in these planes may be adjusted manually to simulate operation at locations of different dip angles. A plastic cover encloses the pickup coils and protects them from injury without in any way impairing their operation. Orientation of the blimp model in accordance with the heading determined by the pilot's steering control is

effected by means of a selsyn receiver mounted on the blimp carriage and driving the column through a set of spur gears. The control signal for the selsyn receiver is obtained from a selsyn transmitter driven through appropriate gear reduction by the blimp rate-of-turn motor drive.

Mechanism to be described below is also mounted on the blimp carriage for use in connection with the simulated bombing system.

As pointed out above, a-c excitation is used for simulation of the magnetic field of the submarine, and the AN/ASQ detectors are simulated by means of simple pickup coils. The output from each of these coils is a 400-cycle voltage, the phase and amplitude of which vary as the coil is carried through the a-c field of the submarine model. The signals from the two pickup coils are fed to separate channels, each comprising a signal amplifier and demodulator and a replica of the a-c amplifier and band-pass filter stages of AN/ASQ-1, in the manner of Chapter 4.

The AN/ASQ click test is simulated in the signal amplifier and demodulator unit by imposing a 400-cycle signal in phase quadrature with the reference signal upon the input of the unit. The click test signal is obtained from the 400-cycle supply and its phase is shifted by means of an RC circuit. A switch is closed to impose the click test signal simultaneously upon the inputs of both channels of the unit.

Output connections directly from the plates of the second amplifier are provided for use with the CM-2/ASQ unit and provision is made for the introduction of background noise of the type generally encountered in the AN/ASQ equipment to the input circuit of the amplifier. Background noise is produced by means of photoelectric cam systems, one of which is provided for each of the port and starboard detection channels. The noise generator unit which includes equipment for both channels is shown in Figure 8. Light from a pair of exciter lamps falls respectively through Y-shaped slits upon a pair of photoelectric cells which are connected across the output of a regulated power supply. Four different optical cams, driven at slightly different speeds, are so positioned in relation to the two slit systems that in the case of each photoelectric cell three cams cooperate to regulate the amount of light falling thereon. The output voltage from each of the photoelectric cells is applied to two cathode follower stages. The background noise level is

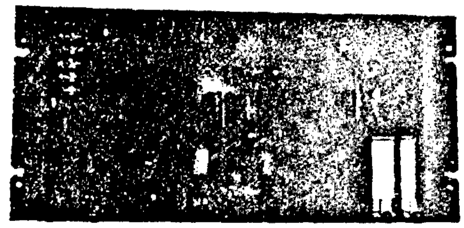


FIGURE 8. Bottom view of noise generator.

adjusted by varying the current in the exciter lamps.

A standard CM-2/ASQ unit is included in the MAT-3 for use in tactical training. The input signals for this unit are obtained from the two detection channels as described above and the output from the unit may be utilized to operate the simulated flare and bomb circuits. Dual wiring is installed so that the CM-2 may be used in either the instructor's or the ARM's position.

7.1.4 Instruments and Indicators

The pilot-trainee is provided with controls and instruments simulating those of an actual blimp, it being noted, however, that in the case of the MAT-3 the pilot-trainee operates the rudder control while air speed and the elevators are controlled by a second person (ordinarily the instructor). The pilot's control position, which is shown in Figure 9, includes an adjustable seat, an instrument panel, a switch box, and a rudder wheel.

The rudder control wheel, which is spring loaded through a heart-shaped cam to simulate the "feel" of a blimp rudder control, operates the center-tapped variable autotransformer which controls the blimp rate-of-turn motor drive. The pilot's instrument panel shown in Figure 9 includes a rate-of-turn meter, a clock,

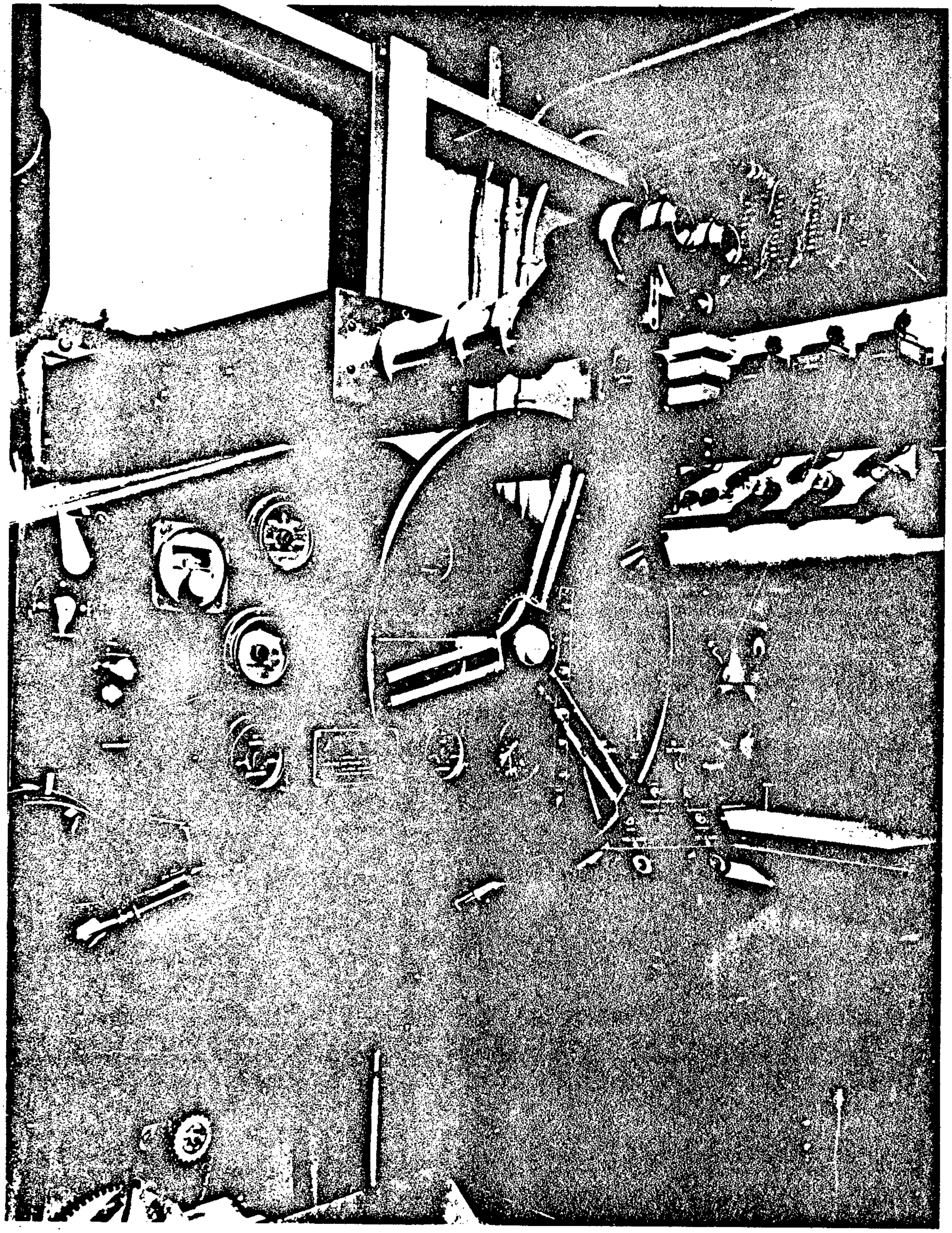


FIGURE 9. Pilot's control position.

magnetic compass, a gyrocompass, an air speed meter, an AN/ASQ sum meter, an AN/ASQ left-right meter, an altimeter, and a rate-of-climb meter.

The switch box includes bomb and flare release switches, switches for controlling the CM-2/ASQ, and pilot lights showing the conditions existing in certain of the control circuits.

An indicating system, shown in Figure 10, is provided to give the pilot-trainee only that information as to his position over the tactics area which he would have available in actual practice. This system takes the form of a scale model of the tactics area, scaled at 1,200 feet to 1 inch, which is movable in respect to a fixed index representing the position of the blimp. This model is mounted on a rectangular-coordinate translation system including an upper and lower carriage which are arranged to travel in mutually perpendicular directions. The lower of these carriages is mechanically linked to the blimp east-west motor drive shaft, while the upper carriage is mechanically linked to the blimp north-south motor drive shaft.

In order to obtain a high degree of realism, the model tactics area is made of cyanite glass the surface of which closely resembles the ocean surface in appearance. This glass is supported by means of a Plexiglas plate in the lower surface of which are recessed concentric cold cathode tubes which provide blue-green illumination and serve to light the ocean surface from beneath. A cyclorama of sand-blasted Plexiglas surrounds the model ocean and is back-lighted by means of conventional fluorescent lamps to simulate the sky.

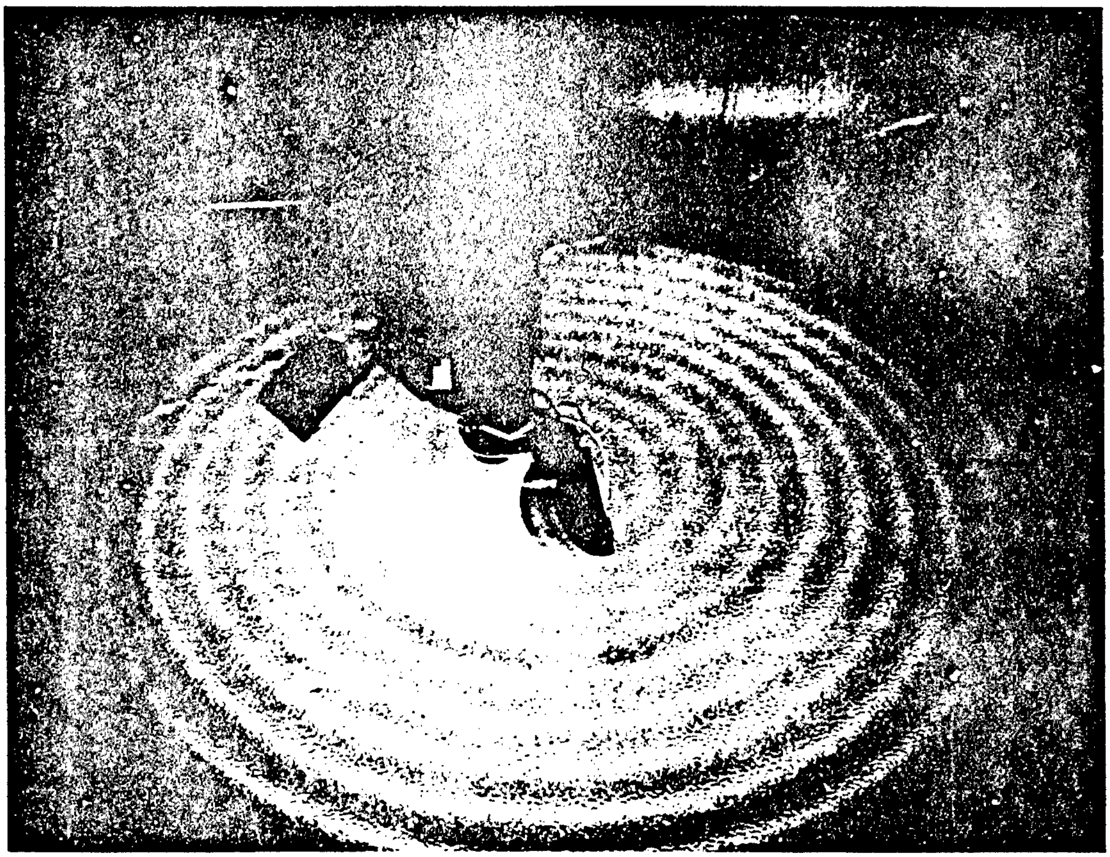


FIGURE 10. Pilot's optical table.

The pilot-trainee is effectively positioned at

the location of the index representing the blimp by means of an optical system[5] the eyepiece of which is located in the pilot's control position immediately above the instrument panel as shown in Figure 9. The optical system comprises a periscope, the lower mirror of which is mounted on the index representing the blimp model, an erecting prism, and a unity power telescope. A binocular eyepiece is provided at the pilot's position. The lower periscope mirror, the erecting prism, and a pair of spot lights which provide additional illumination in the direction of vision are mounted on an optical turret supported over the model ocean, while the remainder of the optical system is mounted between a pair of I-beams extending horizontally across the compartment in which the model ocean is located. The lower periscope mirror is rotated by means of a selsyn receiver so that the pilot's vision is always in the direction in which the blimp is headed. This selsyn receiver is of the differential variety, and one set of its windings is excited from the heading selsyn in the blimp rate-of-turn mechanism. The erecting prism (Dove type) is also driven by this differential selsyn through appropriate reduction gearing which causes its angular velocity to be one-half that of the lower mirror.

The second set of windings of the differential selsyn which drives the optical turret is excited by a selsyn generator, driven through gearing by means of a hand crank on the pilot's instrument panel. This control, known as the "look around," enables the pilot to scan the horizon irrespective of the optical system heading determined by the blimp rate-of-turn drive.

The instructor's position includes controls for both the blimp and submarine models, appropriate blimp and submarine instruments, controls for the field component simulators and the sono buoy simulating equipment. The recording table is also located at this position. The following controls and instruments provided at the pilot's position are duplicated at the instructor's position: the rate-of-turn meter, the magnetic compass, the air speed meter, the altimeter, the rate-of-climb meter, and the blimp rudder control. The blimp speed and altitude are also controlled from the instructor's position.

A recording table, shown in Figure 11, is provided at the instructor's position to indicate the relative paths of the blimp and submarine models in the tactics area and to provide a permanent written record of these paths. This recording table comprises essentially a small model (scaled 1,200 feet to the inch) of the blimp-submarine tactics area on the upper deck of the MAT-3. Translation systems for indexes simulating the blimp and submarine models are driven by cable systems from the blimp-submarine gear box. A sheet of paper, mounted between the recording table carriages representing the blimp and submarine models, is used as the recording surface, and pens mounted on the two carriages of the recording table translation systems make continuous traces of the paths of the two models. The pen on the lower carriage is required to write upside down on the lower surface of the paper and operates through capillary action. The recording paper is translucent, and both traces may be seen simultaneously from above. The recording table also incorporates means for recording the positions of the two models at the instants when flares are dropped or bombing attacks are made.

7.1.3 Bomb and Flare Model Systems

Means are provided in the MAT-3 for simulating the marking flares or floatlights used during tactical operations. For this purpose, mechanism is mounted on the optical turret for depositing a small drop of mercury on the model ocean whenever a flare release is tripped. In addition, the instructor's recording table is so arranged that a mark may be made on the trace representing the path of each of the models whenever a flare is released. This mechanism includes means for translating the paper frame of the recording table through a small circle, thus causing the recording pens to form a circular trace at the positions which they occupy at the time the flare is released. The paper frame is mounted on a torsion rod suspension, and an eccentric cam is arranged to rotate the suspension through a small circle. A heavy clock spring drives the cam through a one-

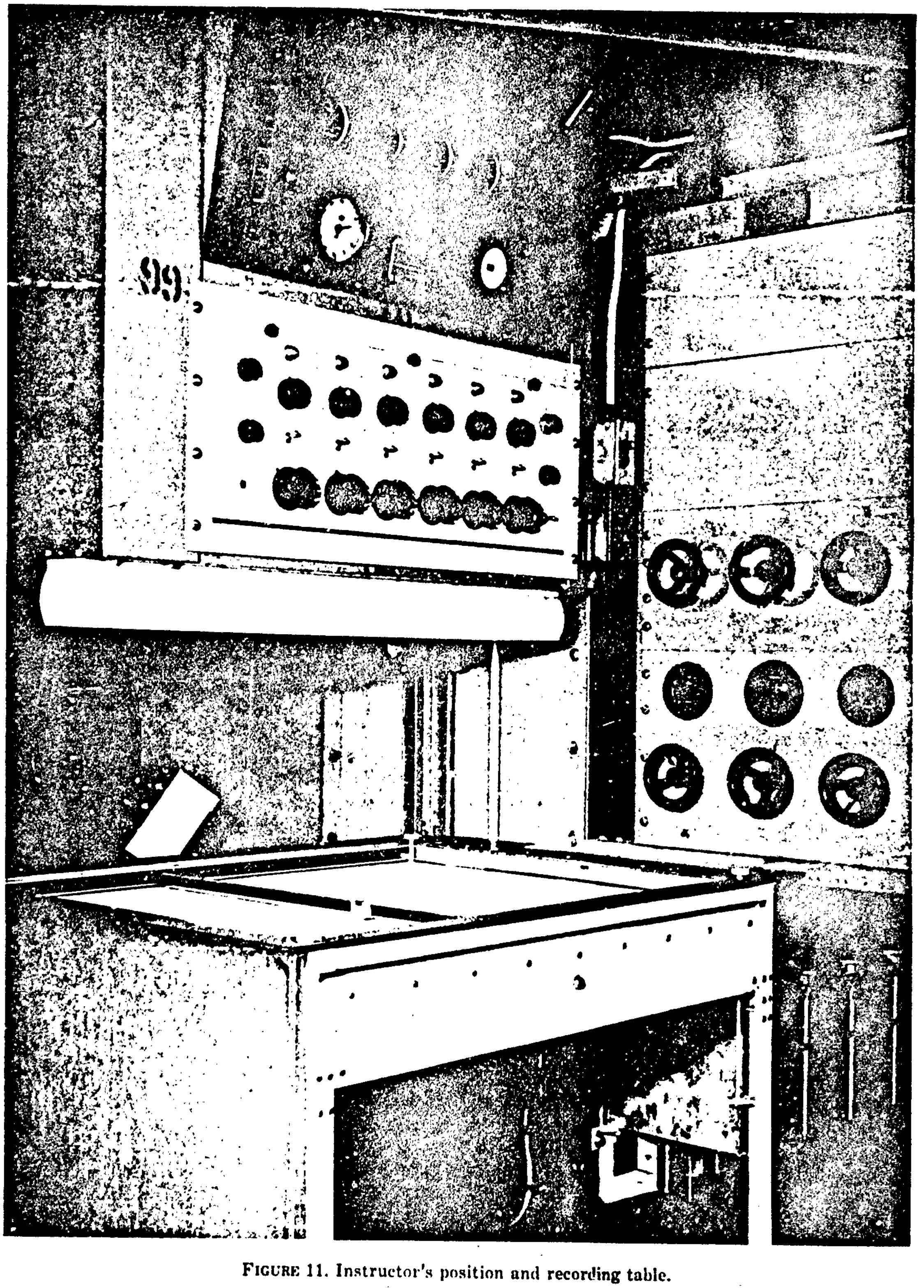


FIGURE 11. Instructor's position and recording table.

revolution clutch which permits one marking operation each time the flare release is tripped. A small electric motor rewinds the spring as required, this motor being stalled when the spring is fully wound.

The MAT-3 also includes means whereby a bombing attack may be simulated and the results of such an attack recorded. The bombs are simulated by means of high-tension sparks which may leap between an array mounted on the blimp model and target wires mounted on the submarine model. Referring to Figure 7, the bomb array is rotatably mounted on the blimp model carriage and comprises a series of parallel needles spaced to represent one stick of the bomb pattern to be simulated. The shaft on which the array is mounted is geared to the blimp-model-supporting column and turns therewith so that the array is always at right angles to the longitudinal axis of the blimp model.

The target model comprises a pair of target wires, one of which is mounted slightly above the other and represents the vulnerable area of the submarine, while the other represents the area surrounding the submarine in which a near hit may be scored. These wires are mounted on a rotatable support which is driven through gearing from the submarine heading selsyn, and the longitudinal axis of the target array is maintained parallel to the fore-and-aft axis of the submarine model at all times.

Means are provided for simulating the dropping of three sticks of bombs at chosen intervals. The high-tension sparks, simulating the bombs, are produced by means of an induction coil through which a capacitor is discharged by means of a thyratron whenever a firing relay is closed by an electromechanical timing system.

The timing system includes an intervalometer which trips the firing relay three times at chosen intervals whenever a bomb release button is depressed. The intervalometer is provided with three mechanical cams mounted for relative rotation on concentric shafts which may then be locked together and driven as a unit by means of an electric motor. A latch engaging a slot in the first cam stalls the electric motor and prevents rotation of the cams until removed. This latch is withdrawn by means of a release relay when the bomb release switch is closed. This relay also closes a pair of contacts which actuate the flare simulator circuits described above; in addition it closes a circuit to a switching relay which connects the hit and near-hit target wires to the first hit and first near-hit indicator channels of the bomb hit indicator to be described below. As the intervalometer shaft revolves, switches associated with the second and third cams are successively closed to send second and third pulses to the firing relay. Simultaneously, additional switching relays are closed to connect the target wire circuits to the second and third hit and near-hit inputs of the bomb hit indicator. The relative angular positions of the three cams may be varied by means of panel controls to vary the spacing between successive sticks of bombs. The first and last sticks may be separated by any time between 0 and 7 seconds and the second stick may be made to fall at any time between the first and third sticks or simultaneously with either of them.

The bomb hit indicator includes three hit indicator channels and three near-hit indicator channels to which the hit and near-hit target wires are respectively connected in proper order by means of the switching relays in the bomb release circuit. The six indicator channels are identical and each includes a thyratron and a pair of neon indicator lamps. One set of indicator lamps is located at the instructor's position while a second set is mounted on the pilot's instrument panel. If the relative positions of the blimp and submarine models when the bomb release is tripped are such that a spark from the bomb array reaches a target wire, it is imposed through an RC delay circuit upon the grid of the thyratron in the proper indicator channel. The threshold of the thyratrons is set by means of a reference voltage obtained from a regulated power supply included in the bomb indicator unit. A canceling relay is operated from a push button on the operator's control panel to remove the plate voltage from the thyratrons, to extinguish thereby any indicator lamps after the score has been determined.

The MAT-3 includes apparatus simulating

the expendable sono buoy detection system so that training in its use in conjunction with the AN/ASQ equipment may be carried on. This apparatus includes means for generating submarine sounds as heard in the sono buoy receiver and also contains means for simulating the hiss background noise commonly heard along with the submarine sounds. Submarine sounds including motor noises and propeller threshing are simulated by means of a partially filled box of barley grains rotated through a gear train by a motor control unit controlled by the submarine speed control. The gear train and the box are mounted in a soundproof enclosure which also includes a microphone. The grinding of the gears and the sounds of the barley grains in the box provide realistic simulation of submarine sounds.

7.2 OTHER TRAINING ACTIVITIES

The Airborne Instruments Laboratory found it necessary to conduct training courses[6] in the operation, maintenance, and tactical use of ASQ equipment. At first this training was done in a rather informal manner and was usually conducted in the field. In the summer of 1943 a school was set up at Mineola to give special ASQ training to Service personnel.

Hangar 7, Roosevelt Field, was partitioned to make available six rooms to the training department. These consisted of an office, two lecture rooms, a room for trouble shooting and maintenance training, a projection room for showing motion pictures and other visual training material, and a large room which was further divided by screens to provide laboratory space for maintenance and construction work as well as space for operator training. In addition, the magnetic attack trainer was used in the training of pilots and operators. The Laboratory airplane was made available for flight training in operation and signal recognition. A sunken tanker off Barnegat Light was used as a target; on special occasions permission was obtained to fly over Ambrose Lightship.[7, 8]

A section of the laboratory room was screened off to make room for the installation of eight AN/ASQ-1 sets complete with CP-2 units. A "duck" or signal simulator and its auxiliary amplifiers, specially constructed to provide signals simulating those obtained with AN/ASQ-1 mounted in TBF, PBM, and PBY airplanes and in lighter-than-air ships, was controlled by the instructor. It could be used as either a single or dual installation. This arrangement made it possible for the instructor to furnish identical signals simultaneously to all students.

In addition to MAT, the pantograph tactics trainer[9] was used. This is essentially a pantograph mounted on a table divided in half with a shield so that a person seated on one side of the table is unable to see the position of the stylus on the other side. The instructor sits on one side to plot the course of the submarine. When the pilot moves his stylus to describe the path of the airplane flying AN/ASQ-1 tactics patterns, the stylus on the instructor's side follows the same pattern, and when it passes over the position of the submarine a contact is reported by the instructor to the pilot. This trainer was used as a preliminary training device.

The compensation trainer mentioned in Chapter 6 consisted of a standard AN/ASQ-1 set together with a TS-7/ASQ perm coil compensating control box, a d-c amplifier, and a cradle allowing rotation about longitudinal and transverse axes to simulate roll and pitch. At the same time the cradle could be rotated about a vertical axis to give any heading. Problems in compensating permanent fields were produced by placing permanent magnets at suitable positions on the cradle. Compensating magnets of the correct strength were adjusted by the student to cancel the fields thus produced. Induced signals were produced by placing Permalloy strips in suitable position on the cradle with appropriate compensation achieved by having the student place other strips in such positions as to cancel these original fields.

Technician Training. This course was designed to cover a period of four or five weeks. It presupposes that the student has had about ten months of previous training. Where it was thought advisable elementary electricity was covered in review, but the actual contents of the lectures and the time spent depended to a

great extent on the student's previous training and experience. Considerable latitude was allowed the student so that he could concentrate on those phases where he seemed to need the most help. All students were required to keep notebooks on laboratory work including detailed analyses of all troubles encountered in the trouble shooting course.

Pilot Training. The pilot training course was designed to give pilots a general background of knowledge in antisubmarine activities and to give them specific and thorough training in the equipment procedures and tactics employed in the field of magnetic detection. It was planned to cover a period of about two weeks.

Operator Training. This course was planned to cover a two-week training period for aircraft radiomen who were to be AN/ASQ-1 or AN/ASQ-2 operators. It included a qualitative explanation of the principles involved, a very thorough training in operational procedures, handling of the equipment, and a general background concerning auxiliary equipment such as sono buoy, radar, and various types of ordnance. During the last two days of this course the operators worked with the pilots on the magnetic attack trainer. This offered a very close approach to actual operating conditions and put emphasis on teamwork and understanding.

In addition to these courses regular flights in the laboratory airplane were scheduled for all pilots and aircraft radiomen at the Mineola Training School.

At the San Diego School where personnel of complete squadrons were trained, the individual crews were given the opportunity of getting used to the particular aircraft they were to operate. To enable them to fly AN/ASQ-1 tactics, in full scale, dropping flares and bombs, a magnetic target was constructed. A piece of 8-inch well casing 20 feet long, filled with approximately 100 half-inch SAE 1020 mild steel rods, was mounted in a wooden frame which could be pivoted about its center. A coil of closely wound No. 12 wire on an aluminum sleeve was fitted over the pipe and connected to a gasoline-driven generator which supplied approximately 750 watts of power to the coil. This produced a magnetic moment of 1.3×10^8 cgs.

In addition to these training activities various members of AIL served from time to time as consultants to the Jam Handy Organization in the preparation of five strip films which were used by the Navy training program for LTA and HTA. These films covered the following aspects.

1. What is MAD?
2. Preoperation check.
3. How it works.
4. Signal characteristics.
5. Flight characteristics.

Another visual training aid in the form of a 16-mm sound-on-film movie entitled "MAD Signal Recognition" was made by the Navy Photographic Unit at Anacostia, D. C. Two members of the AIL scientific staff assisted as technical consultants during the preliminary production stage of this film.

7.3 SUGGESTED ALTERNATIVES FOR AN/ASQ COMPONENTS

The following sections list a number of suggestions for alternatives to parts of the production MAD systems.[10-13] Some of these were merely discussed, while others were tried out on a laboratory scale.

7.3.1 Three Component Detector-Magnetometer

From time to time the suggestion is made that a magnetometer head be designed employing three mutually perpendicular magnetometer elements.[14,15] The complete scheme involves the use of three mutually normal elements, a squaring circuit for the output signal of each element, and provision for adding the squared signals obtained. The obvious advantages of such a sequence of operations is the resulting simplicity and compactness of the magnetometer head due to the elimination of all orientation equipment.

However, certain precision requirements on the aforementioned sequence of operations make such a device difficult of realization. The four principal limitations will be considered separately. The desired maximum error is assumed at about 0.1 gamma in a total field of 50,000 gammas.

Limitation on Orientation of Axes. Take the axes X, Y, and Z in perfect orthogonality. Ideally, the axes of the three elements would lie in coincidence with these three axes. Perfectly linear detection and perfect squaring and summing will be assumed in this case. The maximum allowable disorientation of one axis when computed under these conditions turns out to be 7 minutes of arc.

Allowable Squaring Error. Take the equation

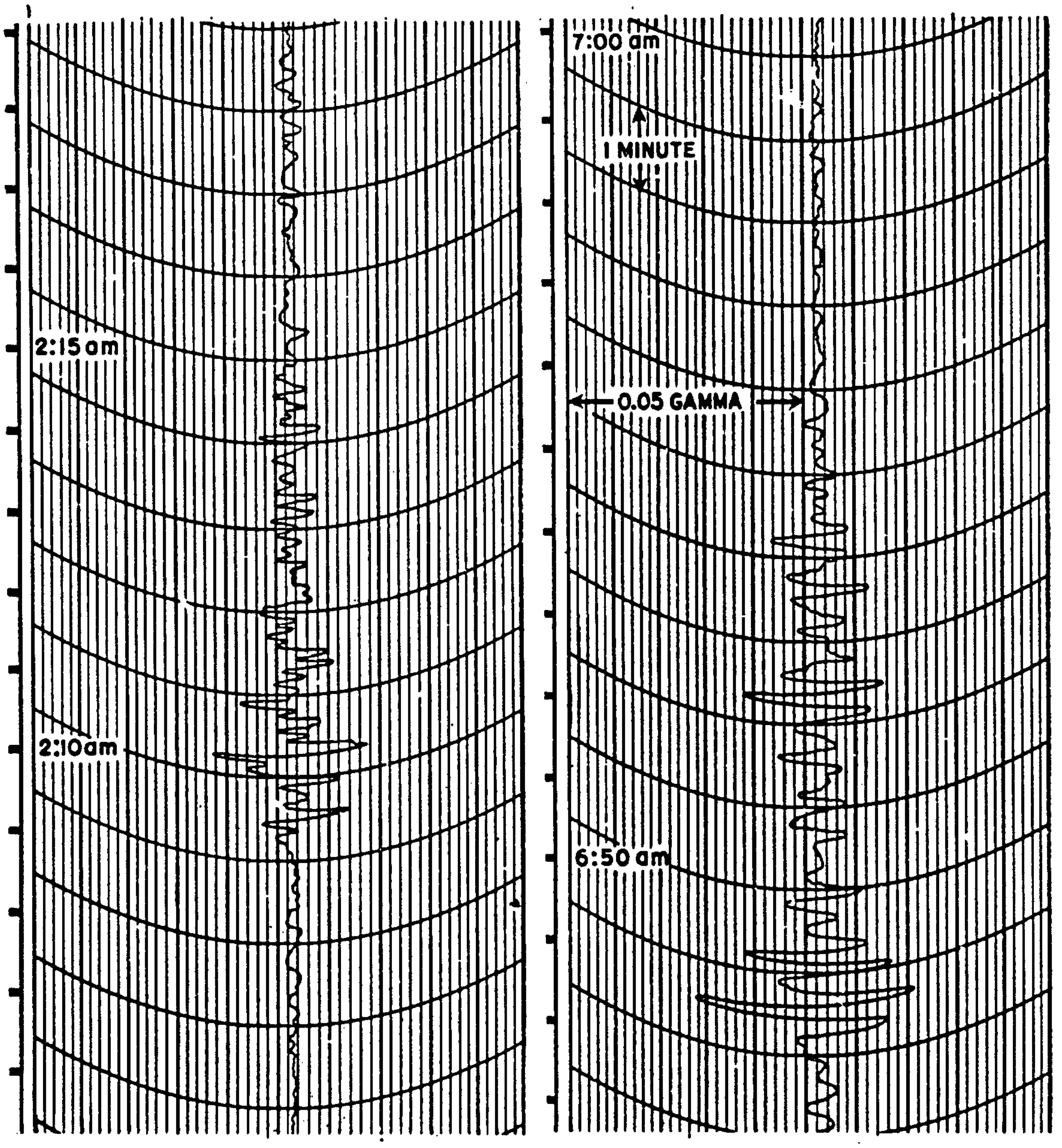


FIGURE 12. Minor magnetic disturbance at Tucson, September 28, 1944.

in the form $S = \sqrt{x^p + y^2 + z^2}$ where p represents an exponent of the x term slightly divergent from 2. Assume perfect orientation of the elements, exact squaring of the y and z

components, linearity of detection in all elements, and proper summing of the squared responses. The allowable error in squaring turns out to be of the order of 0.001 per cent.

Permissible Linearity Error. Take the equation $S = \sqrt{x^2 + y^2 + z^2}$.

As before, assume perfect orientation of the elements, exact squaring of all components, proper summing of the square responses, and precise square root extraction. Consider linear detection in y and z and nonlinear detection in x. The allowable deviation from linearity may then be shown to be of the order of 0.0002 per cent.

Limitation on Summing. Take the equation $S = \sqrt{gx^2 + y^2 + z^2}$.

Here also assumptions are made of perfect orientation of the elements, linear detection in all elements, perfect squaring of all components, proper summing of y^2 and z^2 but not x^2, and precise square root extraction. g differs slightly from unity.

Analysis of this equation shows that the sum should be correct to within 0.0004 per cent of any of the squared terms.

The above considerations will begin to give an insight into the stringent demands on the components of a magnetometer designed along the lines indicated.

7.3.2 Wave-Train Magnetometer

This was an experimental magnetometer,[16] and no research was carried beyond the preliminary breadboard stage. The field-sensitive output of the magnetometer bridge consists of oscillations at a frequency of the order of 10 kc. These oscillations are modulated by the drive frequency (400 c) and its harmonics. The amount of fundamental drive frequency present in the modulation is proportional to the external field and changes phase at zero field, while the modulation is at twice the drive frequency.

The wave trains are obtained by tuning the magnetometer coils with shunt capacity and tuning the output circuit to the same frequency.

A demodulator and amplifier were constructed for use with this magnetometer, and test records taken. The records indicated satisfactory operation, but in view of the existence of suitable magnetometers no further research was done.

7.3.3 Feedback Detector

The purpose of this project was to investigate the effect of a system of degenerative feedback on the performance of a peak-type detector and if possible to develop a simple conversion for the AN/ASQ equipment then in production.

This arrangement exhibited fairly constant sensitivity over a wide range of unbalance, and signals originating in the equipment resulting from filament and plate voltage changes were practically nonexistent. Microphonic disturbances were reduced somewhat and the requirement for accurate selection of components was eased.

The frequency response was found to be about the same as for the AN/ASQ-1. It was found as before that the magnetometer bridge was the main source of noise.

7.3.4 Carrier System for CM-1

In order to eliminate the long time constants of the circuits used for interstage coupling in the CM-1 unit, a new system was developed. The signals from the right and left AN/ASQ-1 units of a dual installation are used to modulate, by means of ring modulators, a 400-c carrier supplied from the oscillator of one of the units. The modulated carrier is then amplified by transformer-coupled amplifiers from which sum and difference signals are obtained. These signals when demodulated serve to operate flare and bomb circuits similar to those in the CM-1 unit. One of these units was built and bench-tested but never underwent a flight test. The system was found to be quite reliable. The modified unit was lighter in weight and required fewer tubes than the one in use. Because of the urgency of other work and the existence of a suitable comparator unit, no further research was done.

7.4 OTHER LABORATORY STUDIES AND EQUIPMENT

Two other special studies carried out by AIL should be mentioned. These dealt with the re-

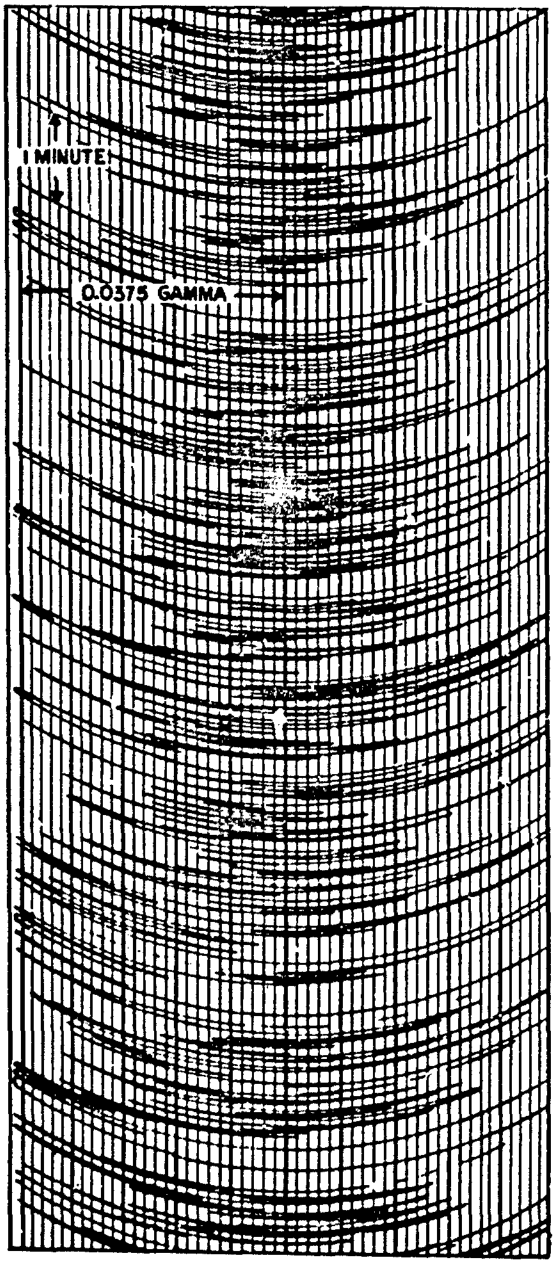


FIGURE 13. Sample of electrical storm at Tucson, about 7:30 p.m., September 12, 1944.

sponse characteristics of various RC filters for signals of the MAD type and with the intensity of fluctuations of the earth's field in the MAD signal frequency range. The results of the former are presented in the references listed in the bibliography.[18-20] The investigation of fluctuations of the earth's field[21, 22] was done in considerable detail, both on Long Island and at the Magnetic Observatory of the U. S. Coast and Geodetic Survey at Tucson, Arizona. Most

TABLE 1. Summary of MAD production and testing done at Airborne Instruments Laboratory, 1942-1944.

Production totals	
MAD Mark IV B-2 equipments (less magnetometer heads)	86
MAD Mark IV B-2 head assemblies	150
MAD Mark IV B-2 motor assemblies	123
MAD Mark IV B-3 equipments (modified Mark IV B-2)	25
AN/ASQ-1 (Mark VI) equipments	170
HG-7 magnetometer head units	23
DT-1/ASQ-1 units	66
DT-1A/ASQ-1 units	4
DT-3/ASQ-1A units	150
DT-3A/ASQ-1A units	51
"U" units (AM-9/ASQ-1A prototype)	20
AM-9/ASQ-1A units	200
"O" and "O-1" units (CP-2/ASQ-1 prototype)	24
CP-2/ASQ-1 units	51
CM-1/ASQ-2 units	73
CM-2/ASQ-2B units	39
"X" units (AM-36/ASQ prototype)	17
AM-9/ASQ units	7
Signal simulator units (TS-160/ASQ-2 prototype)	6
TS-160/ASQ-2 units	6
"Q" units (TS-7/ASQ prototype)	14
Fluxmeter discriminator units CLU-53212	10
CU-36/ASQ-2 units	16
Equipments tested	
Mark IV B-2	476
AN/ASQ-1	170
CM-1/ASQ-2	72
CM-2/ASQ-2B	39
AM-9/ASQ-1A	200
CP-2/ASQ-1	51
DT-1/ASQ-1	89
DT-3/ASQ-1	150
DT-3/ASQ-1A	50

of the charts showed little which could be identified as variations in the earth's magnetic field *at frequencies in the 0.1-c to 1.0-c band.* Figure 12 shows the trace of a minor disturbance as recorded with a band-pass amplifier and the Esterline-Angus recording meter on September 28, 1944. Figure 13 shows a record taken during an electrical storm. Note that the maximum amplitude is less than 0.04 gamma.

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On a typically quiet day the amplitude was less than 0.002 gamma.

Various other items of special equipment proved useful for MAD research. Among these were Helmholtz coils[23] and double-walled Permalloy cans[24] for producing small, magnetically quiet volumes and standard coils designed to be used in place of permanent magnets[25] for calibrating MAD equipment. A fairly elaborate signal simulator (labeled as TS-160/ASQ-2) was also built for production testing and adjustment of the dual CM-1 and CM-2 units.

In addition to the research, development, training, and field installation work described previously, AIL carried out considerable production and testing of Service MAD units. Table 1 summarizes the latter activities. It may be noted that the complete test for an AN/ASQ-1 equipment requires about 15 man-hours.

Chapter 8

USE OF MAD FOR LAND TARGETS

Although ASQ equipment was developed for the detection of submerged enemy submarines, its usefulness is not necessarily limited to this single objective. The equipment has been

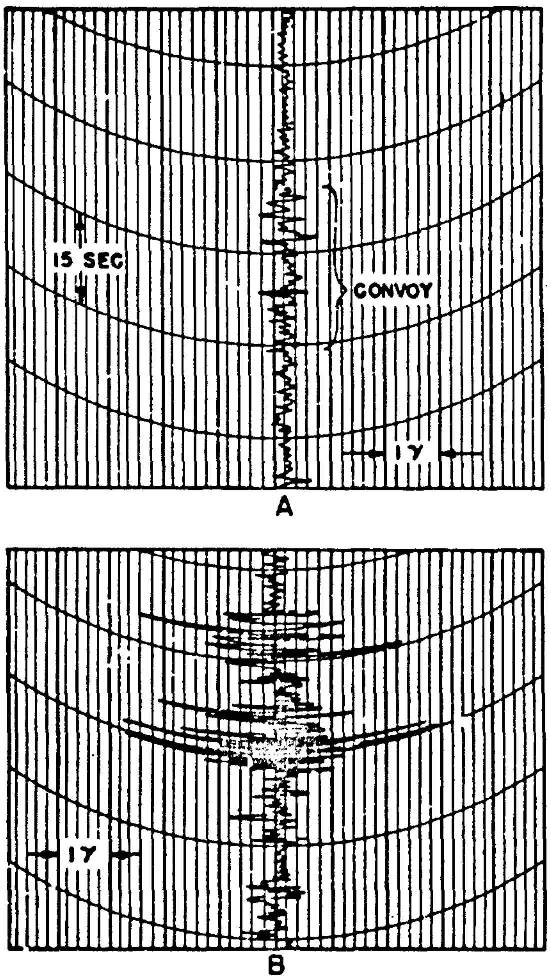

FIGURE 1. Tape record of signals obtained from passage over a convoy of 30 trucks. A. Altitude 150 feet. B. Altitude 100 feet.

used to aid in the search for submerged objects other than submarines. It is logical to consider the use of this equipment for the detection of other iron objects which are obscured from view by darkness, clouds, or camouflage.

A number of test flights have been made to investigate the feasibility of detection of such targets[1,2] as industrial plants, ship yards, mechanical field equipment, and fixed gun emplacements. This chapter describes the result of flights over such ferromagnetic objects at low altitudes as well as the use of AN/ASQ equipment as a navigational aid through the recognition of known anomalies associated with the terrain.

8.1 DETECTION OF MECHANIZED FIELD EQUIPMENT

The large masses of iron in mechanized field equipment[3-5] distort the earth's magnetic field at a sufficiently great distance to be detectable from MAD-equipped aircraft. Although the magnetic effects from motorized equipment are small in magnitude, they are much more sharply

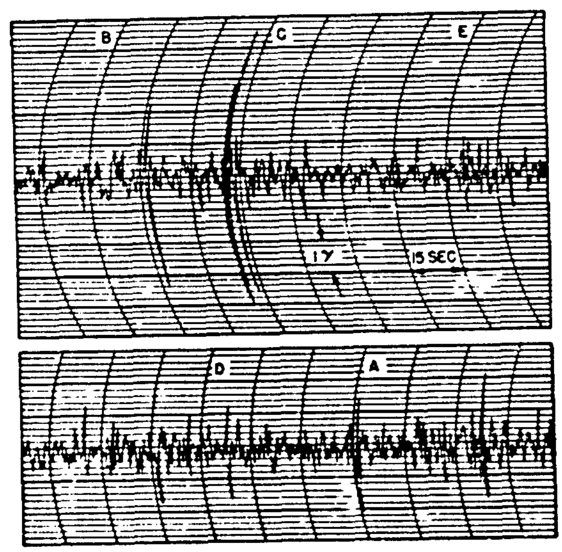

FIGURE 2. Record of signals from search of five areas. Altitude 100 feet.

localized than those from ordinary terrain. To a great extent, the latter can be removed by electrical filters in the MAD apparatus, as modified for use in these flights. Early tests,

which were made over a truck convoy, indicated that operation, at the rather necessarily high speed of the B-25 and at the low altitudes required for satisfactory detection, resulted in faster signals than those for which the AM-1/ASQ unit was designed. Accordingly, these signals were amplified less than the slower ones of geologic and maneuver noise, and detection of small targets with the standard AM-1/ASQ unit was found to be difficult.

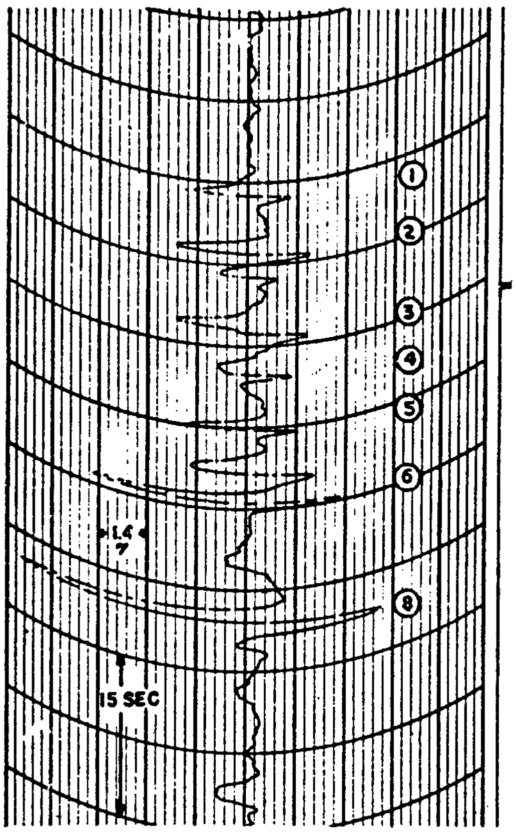

FIGURE 3. Line of mechanized field equipment. Altitude 100 feet. Airspeed 135 mph.

To secure the optimum signal-to-noise ratio, it was necessary to modify the pass band of the AM-1/ASQ unit by decreasing its low-frequency response. The required changes were accomplished by reducing the coupling capacitors in the last two stages of the AM-1/ASQ to 0.1, a switch being provided so that either the normal or the altered band might be used selectively.

Even with the modified amplifier it was found necessary to fly at an altitude of less than 125 feet in order to obtain useful signals from trucks and armored vehicles. Figure 1 shows the tape record of a series of passes made over a convoy of approximately 30 trucks spaced at 30- to 70-yard intervals. In another test, passes were made over five areas identified as areas

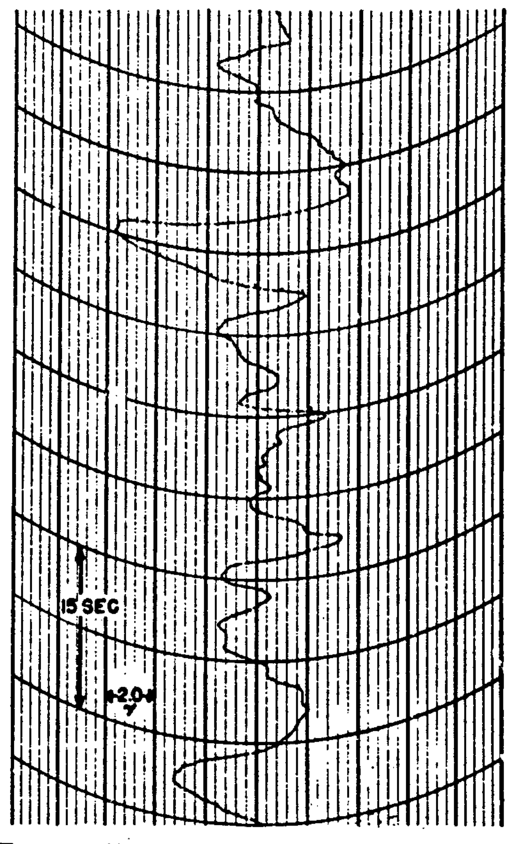

FIGURE 4. Terrain near Port Jefferson. Altitude 100 feet. Airspeed 135 mph.

A, *B*, *C*, *D*, and *E*, which were searched in simulation of an actual tactical situation. One of the areas contained a well-camouflaged tank battalion which was correctly identified as area *C* after passes had been made over all five. The tape records of Figure 2 were made during passes over the five areas and show clearly the basis on which the correct area was identified.

To determine the reproducibility of the signals from several representative pieces of mechanized field equipment, flights were made

repeatedly over units set up in a straight line. These units used were:

1. 4½-inch howitzer M1A1
2. 105-mm howitzer M3A1

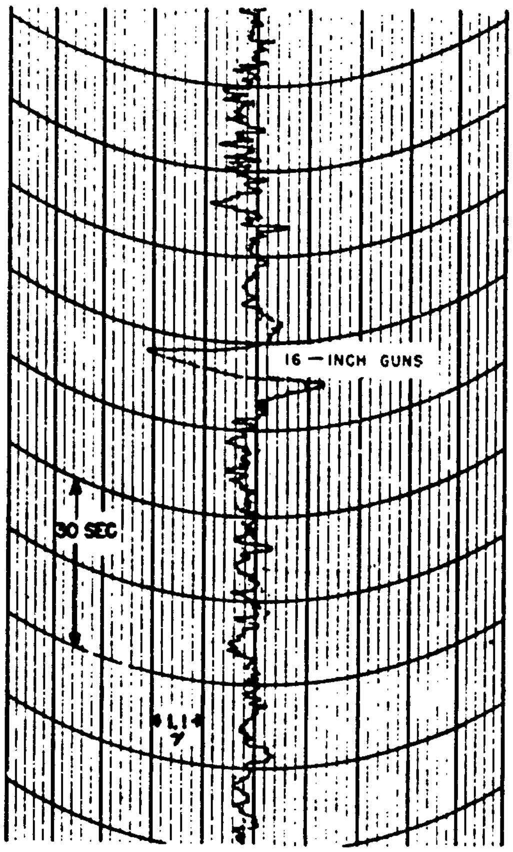

FIGURE 5. Battery of 16-inch guns. Altitude 1,025 feet. Airspeed 135 mph.

3. 155-mm gun M1
4. 40-mm Bofors gun AA, M2A1
5. Half-track
6. Tank destroyer
7. 2½-ton truck
8. 2 tank destroyers
9. Bivouac

The truck (item 7) was considerably out of line with the rest and was missed on all but one pass. Signals obtained for a representative pass over these objects are reproduced on Figure 3. The circled numbers on the charts correspond to the number of the object as tabulated above. The airplane did not always fly directly over all the objects and as a result the signal amplitude for a particular piece of equipment does not always bear the expected relationship to the altitude. It may be noted that the magnetic moment is likely to vary by as much as a factor of four between units of the same type.

Despite their small amplitude, the signals from this field equipment stood out well above the noise level. This is due in part to the magnetic homogeneity of the terrain used.

Figure 4 is a record taken at an altitude of 100 feet over fairly bad terrain just east of Port Jefferson, Long Island. The trace shows slow changes of large amplitude. A set of sharp

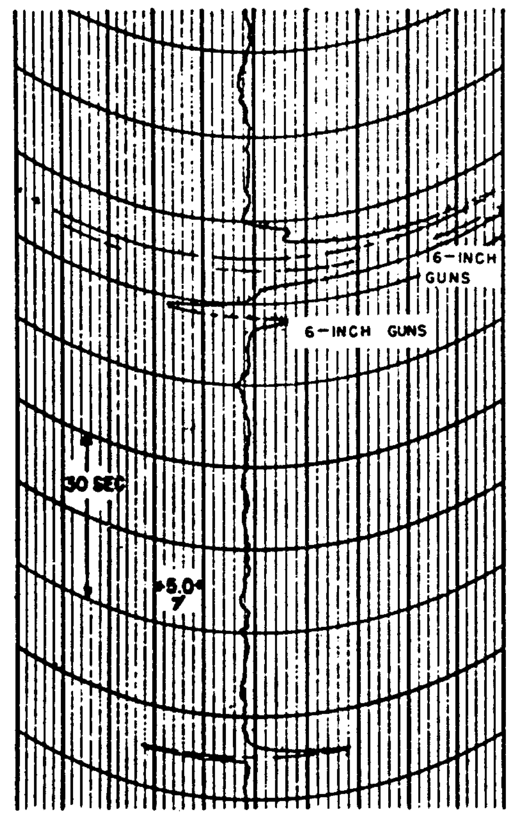

FIGURE 6. Batteries of 6-inch guns and 16-inch guns. Altitude 400 feet. Airspeed 135 mph.

signals, such as those on Figures 1 to 3, superimposed on the traces of Figure 4 could usually be identified as originating from concentrated masses of iron. In this case the magnetic rocks are considerably below the surface. When the

terrain consists of granite, basalt, and volcanic rocks on or near the surface, the effects may entirely mask the signals from mechanized equipment.

The AN/ASQ-1A equipment can be used only to indicate when the searching aircraft is above a target; it cannot be used to guide the aircraft to a target. The principal difficulty in the use of the equipment for this purpose is found in the problem of briefing the navigator with sufficient accuracy to permit location of suspected areas on the first attempt. In addition, conventional navigation methods are difficult to apply with sufficient precision at the high speed and low altitude at which the operation must be carried out.

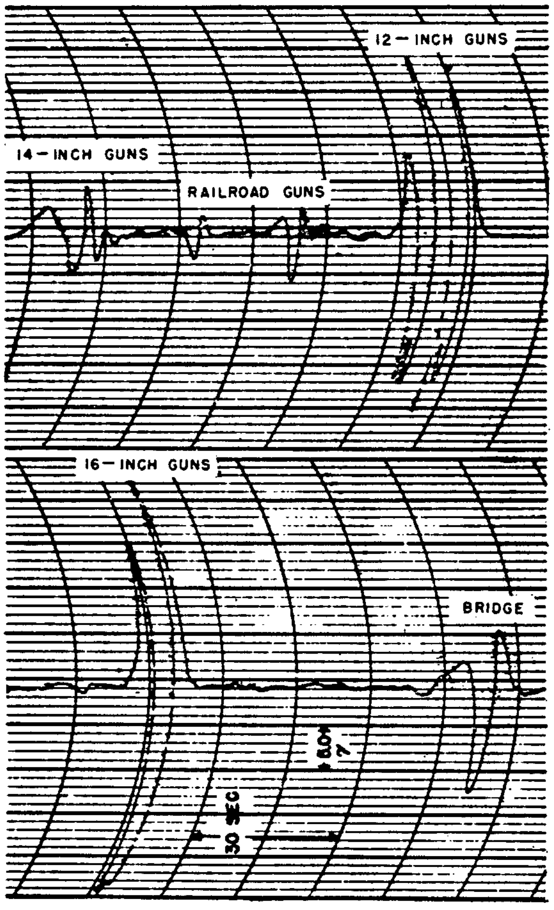

FIGURE 7. Coastal fortifications. Altitude 230 feet. Airspeed 135 mph.

8.2 DETECTION OF COAST-ARTILLERY GUN BATTERIES

Flights were made over the fortifications of Fort Hancock, New Jersey, which consist of two 16-inch guns, two batteries of two 12-inch guns per battery, a battery of two 6-inch guns, and a battery of disappearing 12- and 14-inch guns. Surprisingly large signals and low noise levels were obtained, assuring the detection of the 16-inch guns from an altitude of 1,300 feet. Measurements were made both with the standard detector and with the detector with less low-frequency response. The former is better suited for altitudes greater than 200 feet.

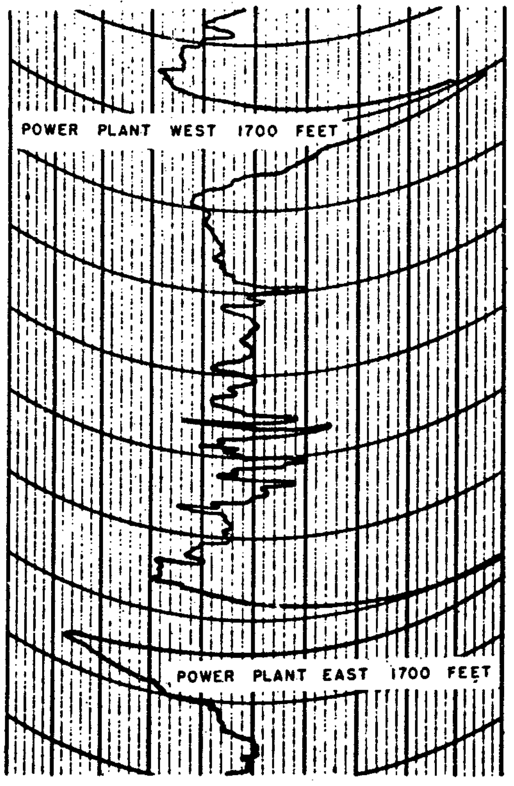

FIGURE 8. Glenwood power plant. Altitude 3,800 feet.

Figure 5 shows the signal obtained with the modified detector while flying at 1,025 feet over the 16-inch guns. At 1,325 feet an identifiable signal was also recorded with the standard detector. The 6-inch guns appear on the trace of

Figure 6. The run shown on Figure 7 was intended to portray what a hedge-hopping aircraft would find while flying over coastal fortifications. The flight path was not always directly over the targets. The objects causing the signals are labeled on the record.

The magnetic moments of the guns were

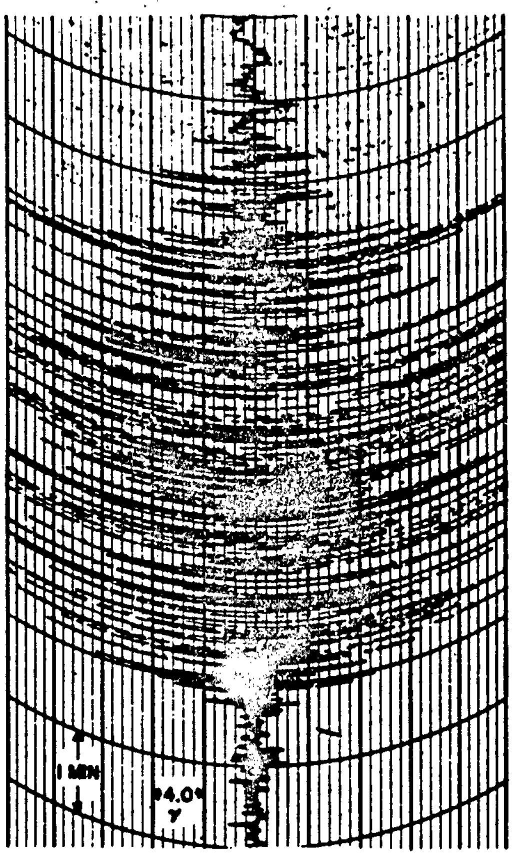

FIGURE 9. Philadelphia. Altitude 1,700 feet.

estimated from extrapolation of the data from model experiments. They are:

16-inch guns	3.4×10^9 cgs each
12-inch guns	3.0×10^9 cgs per battery of two guns
6-inch guns	1.0×10^9 cgs for two guns

The airplane was also flown over a railroad gun and the moment was estimated to be 0.25×10^9 cgs. The battery of 12- and 14-inch disappearing guns gave a signal equivalent to a 0.25×10^9-cgs source. These last two values are questionable; the remaining magnetic moment calculations should be within a factor of two of the actual values. As was mentioned previously, there is little information available concerning the moments of steel structures such as these. However, it is to be expected that, as a result of being fired while parallel to the earth's magnetic field, a gun barrel might acquire a larger permanent magnetic moment than would be expected for other structures of similar size and weight.

8.3 DETECTION OF LARGE STEEL STRUCTURES

Under favorable conditions large steel structures can be detected from altitudes of 3,000

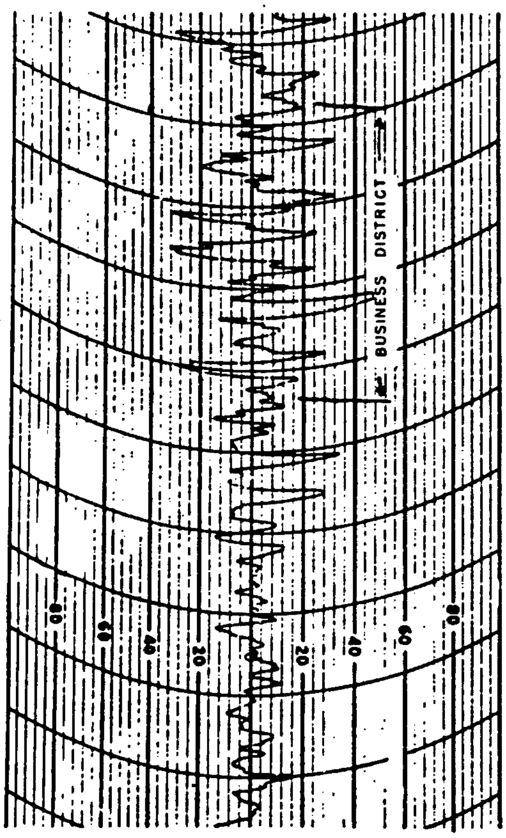

FIGURE 10. Baltimore. Altitude 12,000 feet.

feet. An example of such a structure might be a shipyard, a large steel bridge, or a power plant, which would comprise vertical structural

steel members over 100 feet high. For conditions to be favorable it should be known that magnetic anomalies of geological origin are absent in the immediate neighborhood of the target and that there are no electrical currents creating rapid oscillations of the magnetic field. If geological anomalies are present, the signal from the target may blend into the deflection

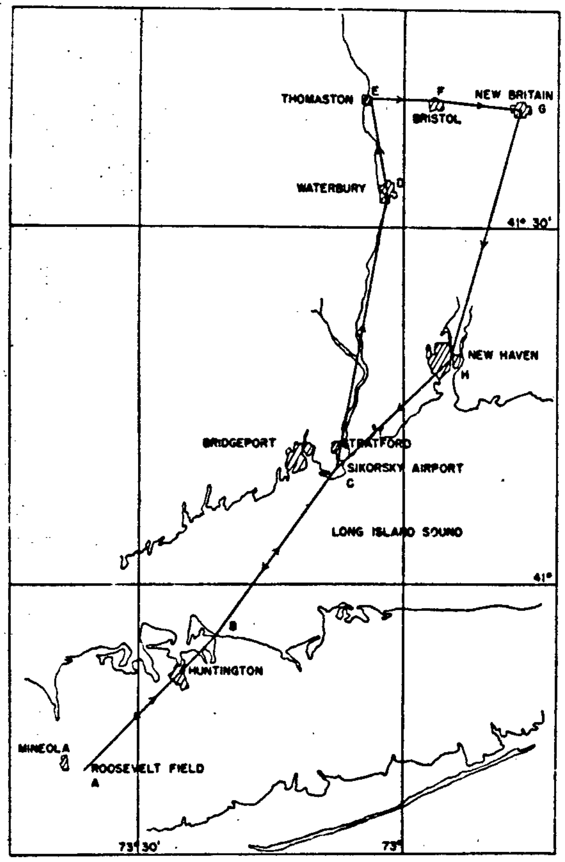

FIGURE 11. Magnetic survey flight.

due to the terrain. Usually enough is known about the geology of enemy territory so that it would be possible to predict whether or not geological anomalies would be troublesome. The detection of large steel targets from altitudes in excess of 500 feet is facilitated by extending the low-frequency response of the ASQ detector.

Figure 8 shows signals obtained over the Glenwood Power Plant, Long Island, at an altitude of 3,800 feet. The slow character of the recorded deflections indicates that they are caused by iron masses rather than by electric currents.

The difficulty in locating a specific structure within a city is obvious from Figure 9 which shows a pass over the center of Philadelphia at 1,700 feet. The transients from d-c power lines completely obscure the effects from steel masses.

8.4 DETECTION OF LARGE CITIES AND INDUSTRIAL AREAS

The detection of large cities[6,7] through the overcast with ASQ equipment from altitudes greater than 3,000 feet depends entirely on the rapid magnetic fluctuations created by electric currents. The maximum altitude from which a large city can be detected by this means is about 20,000 feet. Figure 10 shows signals recorded at an altitude of 12,000 feet during the Army test flights over the city of Baltimore. Records were also obtained over San Diego, New York City, Philadelphia, Baltimore, Washington, New Haven, and Providence. Hartford and Bridgeport, Connecticut, gave no detectable signals from 6,000 feet. A night flight over San Diego showed much smaller deflections over certain parts of the city than were recorded during the daytime, which corroborates the deduction that the disturbances are caused by d-c power systems.

8.5 AN/ASQ AS A NAVIGATIONAL AID

The possibility of the use of the ASQ equipment[a] for navigating bombing aircraft to their targets should be mentioned.[10] Magnetic anomalies of geological origin have patterns much like topographic patterns in a mountainous region. Assume that a navigator is given a topographic map of enemy territory and that he has an accurate absolute altimeter in addition to the barometric altimeter. By plotting terrain clearance while flying above the overcast at a

[a] The Naval Ordnance Laboratory also made some investigation of the possibility of using MAD for geophysical surveying.[8,9]

constant barometric altitude, he should be able to navigate the aircraft to the target area, provided there are some easily identifiable mountain peaks in its vicinity.

The ASQ, with a d-c amplifier on the detector, can be used in very much the same way with a total magnetic intensity contour map taking the place of the topographic map. The preparation of such a magnetic contour map requires a survey of the area by ASQ-equipped reconnaissance aircraft. During the survey a record is taken of the relative total magnetic intensity referred to a given point of departure, and the position of the aircraft is determined continuously or at intervals by photographs of the ground.

A demonstration magnetic survey flight was made from Roosevelt Field into Connecticut at an altitude of 12,000 feet, using an ASQ with a d-c amplifier on the detector. The purpose was to demonstrate that with such equipment magnetic geological anomalies can be mapped to be used as fixed airway markers or beacons roughly lined up with the geological strike of the area. The closed traverse surveyed is shown on the map of Figure 11. The circuit *CDEGHC* was flown over twice. The track of the airplane was plotted by visual observation of the ground without photography or a drift sight and is probably in error by plus or minus one mile. The difference between the magnetic values obtained during the two flights around the circuit are largely attributable to the failure to fly along exactly the same track. Figure 12 is the magnetic profile along the loop *CDEGHC* shown on the map of Figure 11. The circled points are the readings obtained during the first time around the loop. These profiles are similar to elevation profiles of the terrain except that it is the magnetic elevation that is being plotted. Of course, the magnetic intensity does not usually bear any relation to the actual topography, but it does present features fixed with respect to the ground. It should be noted that to be more effective for survey work, the ASQ must be provided with a more stable voltage source for supplying the biasing current to the detector.

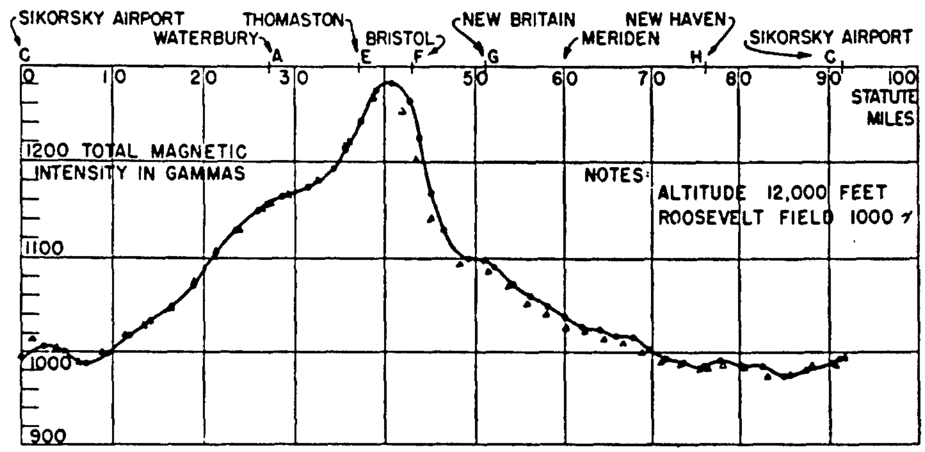

FIGURE 12. Magnetic survey flight signals.

GLOSSARY

AIL. Airborne Instruments Laboratory.

AM-1/ASQ-1. Detector and amplifier circuits of the AN/ASQ-1 system.

AM-9/ASQ-1A. Control amplifier for the DT-3/ASQ-1A and DT-3A/ASQ-1A magnetometer heads.

AM-36/ASQ. Amplifier for use with the eddy-current compensator.

AN/ASQ-1. The final production model of the MAD equipment developed by Airborne Instrument Laboratory.

AN/ASQ-1A. The same as AN/ASQ-1 but using the DT-3 or DT-3A universal magnetometer head.

AN/ASQ-2. A dual installation of AN/ASQ-1 using a CM-1 unit.

AN/ASQ-2A. A dual installation of AN/ASQ-1A using a CM-1 unit.

AN/ASQ-2B. A dual installation of AN/ASQ-1 using a CM-2 unit.

AN/ASQ-2C. A dual installation of AN/ASQ-1A using the CM-2 unit.

AN/ASQ-3. The production model of the MAD system developed by Bell Telephone Laboratories and the Naval Ordnance Laboratory.

ARM. Aviation radioman.

Barkhausen Discontinuities. The small-scale stepwise characteristics of the hysteresis curve for ferromagnetic materials. Believed due to sudden changes in the magnetization of small "domains" within the material.

BTL. Bell Telephone Laboratory.

Click Test. A means of quickly checking the overall performance and sensitivity of an MAD system. An artificial signal is supplied to the system by momentarily changing the value of that current which neutralizes the effect of the earth's field on the detector magnetometer.

CM-1/ASQ-2. Lateral indicator and automatic tripper unit for use in heavier-than-air craft.

CM-2/ASQ-2B. Lateral indicator and automatic tripper unit for use in lighter-than-air craft.

CP-2/ASQ-1. Automatic tripper unit for use with AN/ASQ-1.

CU-36/ASQ-2. A switch box for use with CM-1 and CM-2 units.

Deperming. The process of removing the permanent magnetic moment of a ferromagnetic body.

DT-1/ASQ-1. Magnetometer head and servo motor assembly for the AN/ASQ-1 system. (The "polar head.")

DT-1A/ASQ-1. Same as DT-1/ASQ-1 with improved antishock mounts.

DT-3/ASQ-1A. Magnetometer head and servo motor assembly suitable for use in all latitudes. (The "universal head.")

DT-3A/ASQ-1A. Improved model of DT-3/ASQ-1A.

DY-4/ASQ-1. Power supply for the AN/ASQ-1 system.

Gamma. A unit of magnetic field strength, equal to 10^{-5} oersteds.

Helmholtz Coils. Two coaxial coils of equal diameter spaced in such a manner that current passed through them creates a *uniform* magnetic field over much of the volume between the coils.

HG-7 Head. Magnetometer head used in the Mark IV B-2 MAD.

HG-7A Head. Equivalent to the DT-1/ASQ-1.

HTA. Heavier-than-air craft.

"L" Pad. A network of resistors built into a kit for use in experimental impedance adjustments.

LTA. Lighter-than-air craft.

MABS. Any magnetic airborne bombing system such as AN/ASQ-2.

MAD. Magnetic airborne detection equipment.

Mark I MAD. MAD model developed at the Gulf Research and Development Co.

Mark II MAD. Production model of the Mark I MAD developed at Gulf Research and Development Co.

Mark IV B-1 MAD. First production model of a magnetically oriented MAD.

Mark IV B-2 MAD. Improved production model of Mark IV B-1.

Mark IV B-3 MAD. The Mark IV B-2 system modified to use a single-frequency drive for all magnetometers and with pass band altered for use with automatic units.

Mark V MAD. An experimental model using a magnetically erected gyroscope to orient the detector magnetometer.

Mark VI MAD. The equivalent of the AN/ASQ-1.

Mark X MAD. Equivalent to AN/ASQ-3.

Mat-1. Magnetic attack trainer, original model.

Mat-3. Magnetic attack trainer, improved model.

NOL. Naval Ordnance Laboratory.

"O" Unit. Forerunner of the CP-2/ASQ-1 tripper.

"O-1" Unit. Forerunner of the CP-2/ASQ-1 tripper.

O-1/ASQ-1. Magnetic driver circuits of the AN/ASQ-1 system.

Perm. The permanent magnetic moment of a body.

Permalloy. A series of alloys having high magnetic permeability, usually Ni-fe.

"Q" Unit. Prototype of the TS-7/ASQ.

Radio Sono Buoy. An automatic device, to be floated on the surface of water, which detects and amplifies underwater sounds and broadcasts them in the atmosphere by radio.

RC-132. The Army designation for the Mark IV B-2 MAD.

Selsyn Motor. A type of electromagnetic machine, which causes a controlled rotation through any desired angle in response to an electrical signal.

Spike. A feature of the output voltage curve of the MAD magnetometer bridge. See Section 2.2.1.

Time Index. A feature of an MAD signal record; it is the time taken to record the peak of minimum duration. See Section 3.6.

TS-7/ASQ. The control box of the adjustable perm compensator.

TS-160/ASQ-2. Signal simulator for testing CM-1 and CM-2 units.

"T" Unit. Forerunner of the CM-1/ASQ-2 unit.

"U" Unit. Prototype of the AM-9/ASQ-1A.

"X" Unit. Prototype of the AM-36/ASQ.

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9. *Pantograph-Type Attack Trainer*, NDRC 6.1-sr1129-1380, AIL, July 26, 1944. Div. 6-461-M5
10. *400 Cycle Motors for HG Assemblies*, Jay W. Wright, AIL, Mar. 31, 1943. Div. 6-426-M5
11. *Noise Rejector for O-Unit*, James H. Stein, AIL, May 4, 1943. Div. 6-414-M1
12. *Jacobs Right-Left Indicator*, Jay W. Wright, AIL, Jan. 1, 1943. Div. 6-426-M4
13. *Duplex Detector and Orientor Amplifier Channels*, Otto H. Schmitt, CUDWR. Div. 6-426-M12
14. *Proposed Magnetometer Which Does Not Require Orientation*, W. B. Greenlee, AIL, Oct. 12, 1943. Div. 6-426-M7
15. *Magnetic Airborne Detection System. Tests on Compensating System*, E. P. Felch and T. Slonczewski, Report 2110-EPF-ML, BTL, May 27, 1942. Div. 6-426-M1
16. *Wave Train Magnetometer*, Walter H. Brattain, AIL, Dec. 4, 1943. Div. 6-426-M9
17. *Dzwon's Q-Stabilized Oscillator and Differential Detector*, Judson Mead, AIL, Mar. 3, 1944. Div. 6-426-M10
18. *Investigation of Effect of Frequency and Phase Discrimination on Character of Magnetic Airborne Detection Signals*, C. Richard Evans and Lyman C. Ihrig, AIL, Oct. 15, 1943. Div. 6-426-M8
19. *Analysis of the Parallel-T Network and How It Differs from the Analysis of the Wien Bridge though Both Accomplish the Same Purpose*, Winston C. Backstrand, AIL. Div. 426-M11
20. *RC Filters*, James T. Wilson, AIL, Sept. 6, 1943. Div. 6-426-M6
21. *A Study of Short-Time Fluctuations in the Magnetic Field of the Earth*, NDRC 6.1-sr1129-1769, Service Project NA-120, AIL, Feb. 7, 1945. Div. 6-444-M1
22. [*The Apparatus Used in Measuring the Fluctuations of the Earth's Magnetic Field*], *Project No. 323*, M. R. Winkler, CUDWR. Div. 6-444-M2
23. *Secondary Effect from Helmholtz Coils*, W. B. Greenlee, AIL. Div. 6-414-M5
24. *Magnetic Screening by Thin Shields*, Paul S. Lansman, AIL, Jan. 21, 1944. Div. 6-462-M2
25. *Standard Magnets*, William R. Keye, AIL, July 21, 1943. Div. 6-462-M1

CHAPTER 8

1. [*Equipment for the Detection of Objects Other Than Submarines*], *Report on Project NA-143*, NDRC 6.1-sr1129-826, AIL, Feb. 16, 1944. Div. 6-470-M4
2. [*Equipment for the Detection of Objects Other Than Submarines*], *Report on Project NA-143 (Extension)*, NDRC 6.1-sr1129-826a, AIL, Feb. 7, 1945. Div. 6-470-M7
3. [*Investigation of the Use of AN/ASQ-1A in Detection of Magnetic Land Targets*], *Report on Project AC-82*, NDRC 6.1-sr1129-1768, AIL, Feb. 7, 1945. Div. 6-470-M6
4. *Detection of Armored Vehicles with AN/ASQ-1A in B-25H Aircraft No. 34535*, James H. Stein and P. N. Schwartz, NDRC 6.1-sr1129-1844, AIL, Aug. 26, 1944. Div. 6-470-M5
5. *Signatures of Moving Vehicles*, James T. Wilson, AIL, July 9, 1943. Div. 6-470-M1
6. *Suggestions for the Use of Magnetic Airborne Detection for Bombing Through Overcast*, Victor V. Vacquier, AIL, Sept. 27, 1943. Div. 6-470-M2
7. *Bombing Through Overcast Report for Flight of January 19, 1944*, K. A. McLeod, AIL, Feb. 10, 1944. Div. 6-470-M3
8. *Report on Tests of Geophysical Application of ASQ-3A Equipment*, H. Jensen, Memorandum 6451, NOL, Dec. 19, 1944.
9. *Geophysical Surveying with the MAD*, Report 937, NOL, May 1, 1945.
10. *Profile of Earth's Total Magnetic Field from Jacksonville to New London*, E. M. Hafner, Memorandum 6016, NOL, Sept. 8, 1944.

PRINCIPAL PATENT APPLICATIONS AND INVENTION REPORTS FILED UNDER OSRD CONTRACTS CONNECTED WITH MAD

Contract OEMsr—20
Contractor: Columbia University
Airborne Instruments Laboratory

Inventor	*Title*	*Serial Number*	*Filed*
Donald G. C. Hare	Magnetic Stabilization System	529,003	3/31/44
Victor V. Vacquier John N. Adkins	Directional Indicator System	531,422	4/17/44
Otto H. Schmitt	Compensated Amplifier	521,599	2/8/44
James H. Stein	Bombing Control	543,505	7/4/44
Otto H. Schmitt	Unbalanced Magnetometer	516,612	1/1/44
Henry B. Ribiet	Balanced Magnetometer	534,961	5/10/44
Otto H. Schmitt	Detection System	531,624	4/18/44
Otto H. Schmitt	Orientation System	532,144	4/21/44
Norman E. Klein	Orientation System	543,696	7/6/44
Donald G. C. Hare	Magnetic Incremometer or Gradiometer	532,153	4/21/44
Otto H. Schmitt	Phase Shifter	551,241	8/25/44
Donald G. C. Hare	Filter Network	535,161	5/11/44
Otto H. Schmitt	Torque Amplifier	534,980	5/10/44
Otto H. Schmitt	Magnetometer Compensation System	542,379	6/27/44
Richard Evans	Compensated Magnetometer	543,700	7/6/44
Norman E. Klein	Magnetic Orientation System	535,160	5/11/44
William I. L. Wu	Automatic Release and Reset System	543,494	7/4/44
Otto H. Schmitt	Improved Galvanometer	535,162	5/11/44
W. H. Brattain N. E. Klein M. S. Richardson	Magnetometer Head	535,158	5/11/44
Otto H. Schmitt John H. Hidy	Bridge Compensation System	542,658	6/29/44
Otto H. Schmitt	Training System	548,487	8/7/44
Max S. Richardson	Magnetometer System	543,923	7/7/44
Otto H. Schmitt	Method of Magnetic Investigation	548,492	8/7/44
Otto H. Schmitt Wm. B. Greenlee	Control System	543,592	7/5/44
Edgar W. Adams, Jr.	Recording Method	543,586	7/5/44
Otto H. Schmitt E. G. Sorensen	Indicating System		
Otto H. Schmitt	Motor Control	543,477	7/4/44
James H. Stein	Wide-Latitude Magnetometer	535,159	5/11/44
Walter H. Brattain	Wave-Train Magnetometer	543,924	7/7/44
Ralph F. Norris Robert D. Avery	Shock Mounting	560,450	10/26/44
Otto H. Schmitt Earl G. Sorensen	Translation System	547,478	7/31/44
Robert I. Strough Harry N. Jacobs	Eddy-Current Compensator	542,588	6/28/44
Edgar W. Adams, Jr.	Recording Method	550,323	8/19/44
Otto H. Schmitt G. S. Dzwons	Bomb Simulator	558,408	10/12/44
Otto H. Schmitt	Tripper System	547,477	7/31/44
Norman E. Klein Walter H. Brattain	Integral-Driven Magnetometer Head	543,697	7/6/44
James H. Stein	Selective Automatic Missile Release	548,578	8/8/44
Wilmer C. Anderson	Magnetometer System	542,493	6/28/44
Otto H. Schmitt	Self-Oscillating Magnetometer	542,844	6/30/44
Otto H. Schmitt	Demodulator		
Otto H. Schmitt	Combination Magnetometer and Gradiometer	555,538	9/23/44

PRINCIPAL PATENT APPLICATIONS AND INVENTION REPORTS FILED UNDER OSRD CONTRACTS CONNECTED WITH MAD—(*Continued*)

Inventor	*Title*	*Serial Number*	*Filed*
Wilmer C. Anderson Robert I. Strough	Induced Magnetization Compensator	547,448	7/31/44
Walter E. Tolles	Eddy-Current Compensator	549,433	8/14/44
William I. L. Wu	Electronic Switching Detection System	549,435	8/14/44
William I. L. Wu Victor V. Vacquier	Adjustable Orientation System	549,434	8/14/44
Walter E. Tolles	Compensation of Inductance Magnetic Fields	547,447	7/31/44
Walter E. Tolles	Product-Taking System	551,238	8/25/44
Walter E. Tolles	Magnetic Field Compensation System	548,579	8/8/44
James H. Stein	Maneuver Monitor	548,577	8/8/44
Otto H. Schmitt	Phase-Shift Magnetometer	548,488	8/7/44
Wilmer C. Anderson	Compensator for Induced Magnetic Field	547,449	7/31/44
Otto H. Schmitt	Magnetometer	548,485	8/7/44
Otto H. Schmitt	Dual Amplification System	548,491	8/7/44
Otto H. Schmitt	Voltage-Regulator System	548,486	8/7/44
Otto H. Schmitt	Thermal Demodulator	548,489	8/7/44
Otto H. Schmitt	Varistor Demodulator	548,490	8/7/44
	Contract OEMsr—27 Contractor: Gulf Research & Development Company		
Ralph D. Wyckoff	Air-Jet Apparatus for Orienting and Stabilizing Apparatus	603,309	7/5/45
	Contract OEMsr—34 Contractor: General Electric Company		
Albert W. Hull	Methods and System for Magnetic Field Investigation	479,713	3/19/43
	Contract NDCrc—99 Contractor: Gulf Research & Development Company		
Victor Vacquier	Apparatus for and Methods of Responding to Magnetic Fields	403,455	7/21/41
Victor V. Vacquier Gary Muffly	Method and Apparatus for Measuring the Values of Magnetic Field	508,550	11/1/43
	Contract OEMsr—367 Contractor: Western Electric Company		
Edwin P. Felch, Jr. Thaddeus Slonczewski	Magnetic Field Strength Indicator	483,754	4/20/43
Edwin P. Felch, Jr. Thaddeus Slonczewski	Magnetic Field Strength Indicator	483,755	4/20/43
Thaddeus Slonczewski	Magnetic Field Strength Indicator	483,756	4/20/43
Winthrop J. Means	Orienting Device	496,833	7/30/43
Thaddeus Slonczewski	Detection System	618,551	9/25/45
	Contract OEMsr—967 Contractor: Western Electric Company		
A. G. Laird T. Slonczewski	Magnetic Field Detector	555,058	9/21/44
	Contract OEMsr—1129 Contractor: Columbia University Airborne Instruments Laboratory		
Donald G. C. Hare	Inverse Modulation Detector		
Donald G. C. Hare	Low-Frequency Amplifier		
Donald G. C. Hare	Compensated Locator		
George S. Dzwons	Stabilized Amplifier	558,413	10/12/44
Otto H. Schmitt	Oscillator	549,524	8/15/44
Otto H. Schmitt	Wave-Train Detector	549,450	8/14/44
Walter E. Tolles	Eddy-Current Compensation	550,415	8/21/44

PRINCIPAL PATENT APPLICATIONS AND INVENTION REPORTS FILED UNDER OSRD CONTRACTS CONNECTED WITH MAD—(*Continued*)

Inventor	*Title*	*Serial Number*	*Filed*
Wesley A. Fails	Position Indicator		
Jay W. Wright	Signal Recognition Trainer		
Otto H. Schmitt	Noise Generator	550,476	8/21/44
Otto H. Schmitt	Recording Indicators	551,242	8/25/44
Wilmer C. Anderson	Magnetometer Compass	551,173	8/25/44
Otto H. Schmitt	Flight Trainer	559,784	10/21/44
Norman E. Klein	Planetary Movement	551,236	8/25/44
Donald G. C. Hare	Emission Stabilized Amplifier	574,592	1/25/45
Donald G. C. Hare	Sonic Tiltometer	578,772	2/19/45
Wilmer C. Anderson	Tiltometer System	578,771	2/19/45
Walter E. Tolles	Compensation of Aircraft Magnetic Fields	552,516	9/2/44
James H. Stein	Antihunt System	560,460	10/26/44
Wilmer C. Anderson	Improved Magnetometer Compass	567,394	12/9/44
Kenneth A. McLeod	Portable Magnetometer	583,747	3/20/45
Russell R. Yost, Jr.	Gain Control	613,147	8/28/45
Robert F. Schulz Russell R. Yost, Jr.	Improved Fluzmeter-Recorder		
Otto H. Schmitt	Stabilized Oscillator		

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-20	The Trustees of Columbia University in the City of New York New York, N. Y.	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-1129	The Trustees of Columbia University in the City of New York New York, N. Y.	Conduct studies and experimental investigations in connection with the development and research work involving the application of magnetic methods to anti-submarine warfare including the development of airborne equipment and methods for training personnel in the use of such magnetic methods, establishing the necessary laboratories and facilities for this purpose.
OEMsr-40	Western Electric Company, Inc. New York, N. Y.	Experimental studies and investigations of the development of equipment and methods for detection of submarines by magnetic effects.
OEMsr-367	Western Electric Company, Inc. New York, N. Y.	Studies and experimental investigations in connection with the detection of submarines by magnetic methods.
OEMsr-967	Western Electric Company, Inc. New York, N. Y.	Studies and experimental investigation in connection with the phenomenon of MAD.
OEMsr-34	General Electric Company Schenectady, N. Y.	Development of equipment and methods for detection of submarines by magnetic effects.
OEMsr-27	Gulf Research and Development Company Pittsburgh, Pa.	Studies and experimental investigations in connection with the development of equipment and methods applicable to the detection of submarines by magnetic effects, including magnetic airborne detection.
OEMsr-315	Goodyear Aircraft Corp. Akron, Ohio	Studies and experimental investigations looking toward the development of streamlined serial housings for magnetic detection equipment, including windtunnel and aircraft tests.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, National Defense Research Committee [NDRC], from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
AC-82	Special MAD project for Fifth Air Force.
NA-120	Magnetic detection form aircraft.
Ext. NA-120	Arrangements for measurement of time variations in the magnetic field of the earth.
Ext. NA-120	Construction of a magnetic attack trainer.
Ext. NA-120	Requirements for CM-2/ASQ-2B equipments (39).
Ext. NA-120	Four sets of bulk spares for the CM-2/ASQ-2B equipments.
Ext. NA-120	Request for six AN/ASQ-1A towed birds.
Ext. NA-120	MAD "Bird" for naval airship training and experimental command.
NA-143	A preliminary investigation of the possibilities and limitations of using MAD for BTO.
NS-230	Reduction of interference on magnetic detection loops.

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.